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EVALUATION OF EVAPOTRANSPIRATION AND THE EFFECT OF DIFFERENT LEVELS OF IRRIGATION ON TUBER YIELD AND QUALITY OF THREE POTATO VARIETIES USING A LINE SOURCE IRRIGATION DESIGN

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James McE. Jenkins

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Maurice L. Vitosh
Major professor

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James McElvain Jenkins

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ABSTRACT

EVALUATION OF EVAPOTRANSPIRATION AND THE EFFECT OF DIFFERENT LEVELS OF IRRIGATION ON TUBER YIELD AND QUALITY OF THREE POTATO VARIETIES USING A LINE SOURCE IRRIGATION DESIGN

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The effect of irrigation level on the yield and quality of three potato varieties (Superior, Atlantic and Russet Burbank) was evaluated using a line source sprinkler system. Concurrently, evapotranspiration rates were measured and compared with those estimated by a prediction equation in use at Michigan State University.

During the 1981 growing season the equation was found to overestimate weekly evapotranspiration. The error is likely due to a lack of measured weather data and the short length of the estimation period. Each variety could take some reduction in water application without significant yield losses but the trends strongly suggested that any reduction in water produced lower yields. Generally, irrigation had no effect on the potato's internal quality. The amount of irrigation water applied did effect the percentage of knobby tubers in the Russet Burbank variety. There was a 46% increase in knobby tubers between the maximum and minimum irrigation treatments.

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INTRODUCTION

In many parts of the country the number of irrigated acres of land is increasing rapidly. There are a number of reasons for this increase; among them, significant increases in yield and in some cases crop quality (particularly on soils with low moisture holding capacities); minimization of year to year risk due to variable weather conditions; and an improved effectiveness of fertilizers, herbicides and pesticides. The benefits of irrigation are accompanied by various drawbacks. Irrigation is an expensive production practice, both in terms of the initial investment as well as the on-going cost of operation. It also requires a high level of management if the maximum benefits and financial returns are to be realized.

Michigan has seen somewhat of an irrigation explosion in the past 13 years. From 1969 to 1978 the number of irrigated acres increased from 70,000 to 226,000, and today the number is over 400,000 (98). This accounts for 5.5% of the total harvested land and the expansion is expected to continue at an annual rate of 20% through the year 2000 (92).

In Michigan, potatoes account for about 0.55% of the 7.3 million acres of land under agricultural production. Of this 40,000 acres in potatoes, about 33,700 of them are being irrigated. Thus, over 84% of the potato acreage is being irrigated, representing 8.4% of all the irrigated land in Michigan. This makes clear the need for accurate information on which to base irrigation management decisions for potatoes.

The major kind of information which is needed involves two main areas. The first is irrigation scheduling. Accurate scheduling of irrigation water can only be done with reliable estimates of the evapotranspiration for the potato crop and the amount of water remaining in the soil. The second area is crop response to different moisture levels. This encompasses potato yield and quality depending on the timing and amount of water applied.

A problem that has been observed among some Michigan irrigators is the failure of the irrigation systems to keep up with crop evapotranspiration during peak use periods. There are a number of possible reasons for this. It may simply be due to underestimating the rate of evapotanspiration. Less easily corrected causes may be undersized pumps and wells or the need for irrigation rates which are higher than the soils infiltration rate.

A contributing factor common to center pivot systems in Michigan is an obstruction in the field which prevents the completion of a full circle (i.e. a house or a barn in the field). This may necessitate running tne system back around empty, which is time consuming, or irrigating back in the opposite direction. Back irrigation complicates selection of application rates and may not be feasible for some heavier soil textures. Failing to keep up with evapotranspiration results in a slowly increasing soil moisture deficit. Only the fortuitous occurance of rainfall during these deficit periods will prevent soil moisture depletion.

The objective of this study was two-fold. First, to examine the effect of different levels of irrigation on potato yield and quality. Secondly, to experimentally determine the evapotranspiration rate of potatoes during peak use periods. These evapotranspiration measurements are needed to verify the accuracy of a prediction equation which is in use in Michigan. In the face of rising production costs, this knowledge will allow those growers who are presently irrigating to move toward full production potential using water and energy resources most efficiently.

LITERATURE REVIEW

Estimating Evapotranspiration

The past half century has seen an enormous amount of research done on evapotranspiration (ET). In part, this intensity of study is due to transpiration playing a central role in numerous plant processes, but the major impetus has been the rapid expansion of irrigation into almost every area of agriculture. Because irrigation is a consumptive use of water, it can create a marked stress on the water resources of an area. Limited water resources in many areas, along with the fact that most methods of irrigation are energy intensive, make efficient irrigation practices essential. It is this quest for efficiency, the need for accurate quantitative estimates of water loss, which has brought ET under such close scrutiny.

Water Balance

The first and most natural approach to determining ET is by maintaining some form of water balance. This involves measuring incoming water, primarily rain (R) and irrigation (I), outgoing water due to runoff (O) and deep drainage (D) and changes in the stored soil water (S). A water balance equation for calculating ET might look like:

$$ET=R+I-(S+O+D)$$

There is no need to say what forces are driving each process, only how much water was lost to each. Generally, weighing lysimeters are the most accurate and reliable means of assessing soil moisture changes

(54,80) but they are available for use in relatively few areas. Nonweighing lysimeters will quantify the amount of water lost to deep drainage but the changes in the soil moisture content still must be measured in some manner. Normally, assumptions are made concerning how much water is lost to runoff and drainage while measuring the changes in soil moisture. Based on these assumptions, the balance of the losses are ascribed to ET. The difficulty of accurately determining the amount of water lost to drainage and runoff has caused some people to question the validity of the water balance procedure. If the runoff and drainage errors are acceptable, however, measurements of soil water depletion can be used (80).

Measurement of Soil Moisture

Gravimetric Method

There are a number of methods which are employed to measure soil moisture content. The oldest and most common of these techniques is gravimetric sampling. This method will provide good, reproducible results but it is laborious and time consuming. Numerous samples must be taken at any one time to give a representative estimate of the soil moisture content for a given area. In addition, sampling is a destructive procedure so samples cannot be taken from the same place twice. There is also the need for the additional measurment of the soil bulk density if the gravimetric results of percent moisture by weight are to be converted to the more useful percent moisture by volume.

Tensiometers

Tensiometers are an indirect method of measuring changes in soil moisture content. These instruments measure soil moisture tension which is related to the moisture content. The conversion of the tensiometer readings into percent water by volume requires an experimentally determined soil moisture characteristic curve. This is one of the major disadvantages of using the tensiometers to measure changes in soil moisture content. Each soil has a unique soil moisture characteristic curve (29) and the procedure for constructing these curves is tedious (61).

Another limitation of the tensiometer is that it has only a small range of moisture tension which it can measure, 0–0.8 bars. In view of the range of tension at which plants can remove water, generally believed to be 0-15 bars (62), tensiometers may not appear very useful but in fact they have wide application. This is because for the majority of irrigated agricultural soils, the tensiometer's range accounts for more than 50% of the soil water available to plants (29). In addition, when using tensiometers, irrigation is usually prescribed based on soil moisture tension rather than content so the characteristic curve is not needed (9,77).

As with gravimetric measurements, replication of tensiometers is needed to give a reasonable estimate of the average soil moisture present within a given area (18,91). Dylla et. al. (18) recommends a minimum of 10 tensiometers at 20 to 22 cm in a shallow (61 cm) uniform soil. If the soil is deeper or if there are significant variations in soil type, the number of instruments that are needed may increase. The depth at which tensiometers are set will be determined by the rooting depth of the crop. The depths should be chosen to give a good representation of soil moisture in the major zone of root proliferation.

Neutron Scattering

A third method of determining soil moisture content, and possibly the most preferable (80), is by means of neutron scattering via the neutron probe. Because the thermalization of fast neutrons in the soil is almost linearly related to the volumetric water content (29) a procedure for determining water content is possible. Over the past 25 years this technique has gained wide acceptance as a sound means for making moisture measurements (29,31). Some of the advantages of the neutron probe are that it is fast, nondestructive, able to measure a large volume, and the water volume fraction is determined directly. It allows repeated readings at the same locations and depths over time, so that the only significant variable becomes the changing water content. In spite of the advantages, the neutron probe will probably remain primarily a research instrument due to the high initial investment and the accompanying radiation hazard.

The procedure for calibrating the neutron probe has been the subject of much investigation and has produced many differences of opinion. There is common agreement that soils having significant levels of elements with a high capacity for absorbing neutrons (Boron, Cadmium, Chlorine) need special consideration when calibrating a neutron probe (29,31). With those soils excepted, many investigators feel that one calibration curve will serve most mineral soils (25,79). Others conclude that two curves are needed, one for loam and sand, and one for clay soils (52). The most conservative researchers suggest that the probe needs to be calibrated for each soil type and set of circumstances (29). If the probe is used to follow changes in soil moisture rather than absolute water content, one calibration curve has much wider application. This is because each reading will carry the same error, which then cancels out (75).

Manufacturers of the probe normally provide a calibration curve which was determined in the laboratory. This may usually be used in the field, provided the specifications for the access tubing are followed (25). Improvements in the manufacturers calibration procedures (84) may increase the usefulness of the calibration curve which they supply. Nevertheless, the majority of researchers would agree that for use in the field, a calibration curve determined in the field is superior to one prepared in the laboratory (29,80).

Deterministic and Empirical Models

Energy Balance

A second major approach to estimating ET involves the development of prediction equations. These equations can be derived in one of two ways. The most theoretical approach is to model the forces which drive and govern ET. This is sometimes referred to as an energy balance model. By then measuring the various factors involved, estimates can be made as to the quantity of water lost to ET. Due to the similar nature of the two processes, these deterministic models are largely extensions and modifications of equations for predicting evaporation from a free water surface (57,73).

Empirical Correlations

In spite of the relative success of the energy balance models in predicting ET, their use in the original form is limited due to the general unavailability of some of the required weather data (i.e. solar radiation, vapor pressure deficit, wind run, etc.). This practical limitation has made more empirical methods popular. The correlation of available climatological measurements with ET is the most widely applied approach for predicting ET losses (10,71,73). Climatic factors such as maximum and minimum temperature, mean daily temperature, and length of day are most frequently used in these equations (71,80,89). Included in these empirical methods are the energy balance models with the unavailable climatic data estimated in some way (80). Some investigators have reservations about this type of empirical approach on theoretical grounds (80,89), but a number of these derived equations have proven to be useful within certain limits (71,73,86).

The conditions that restrict the use of empirical formulae have to do with the limited nature of their calibration (68,73,80). The calibration is affected by factors such as latitude, local climatic conditions, surrounding terrain and crop type. Care must be taken when applying empirical equations to locations, circumstances of time periods other than those for which they were first derived. Some way of empirically verifying the estimated ET is essential any time one of these equations is used in a new situation (73,80).

Errors

It is difficult to say how much in error the prediction of a particular equation is. For the empirical methods, even when great care is taken, errors of 15-25% and more are possible. When using the energy balance equations with all the parameters measured, errors of 10-15% can be expected. The errors for both of the above general approaches are likely to increase as the period of estimation becomes shorter. Only with a sensitive weighing lysimeter is it possible to bring error down to the 5% level over periods as short as 1-2 days (11,80).

Potential Evapotranspiration

Most ET models will give some estimate of "potential evapotranspiration" (ETp). The traditional definition of this term is the "evaporation from an extended surface of short green crop, actively growing, completely shading the ground, of uniform height and not short of water" (89). Van Bavel (88) later generalized ETp suggesting that "when the surface is wet and imposes no restrictions upon the flow of water vapor, the potential value of evapotranspiration is reached."

Because of ambiguities in the definition and application of the term ETp, particularly in arid areas, some feel that a reference ET (ETr), with the reference crop specifically noted, is more useful (97). Both ETp and ETr are measures of a maximum rate of ET.

Grass and alfalfa are the most commonly used reference crops (97). The reference crop ET is the standard against which the ET of other crops are compared. Doorenbos and Pruitt (14) give the traditional definition of ETp for ETr but they make specific note of "an extensive surface of 8-15 cm tall green grass cover" as being the crop in question.

Crop Coefficients

In practice the ETr is related to the ET of other crops (ETc) by some experimentally determined crop coefficient (Kc). The crop coefficient can be calculated by measuring both ETr and the ET of a specific crop, preferably concurrently, and then setting them in terms of a ratio. It is important to note that the Kc will change depending on the reference crop (8,97). The form this equation usually takes is:

$$Kc = ETc/ETr$$

The crop coefficient will change over the course of the growing season (16,17,35) depending on the physiological development, percent crop cover and climatic conditions. The other factors apparently are assumed to be negligible over the course of the growing season. By plotting the changing Kc values over time a "crop curve" can be developed. This curve reflects the changing water use by the crop over the growing season. When the development of this curve is complete it is possible to use it to calculate ETc. By using a prediction equation and the available climatic data to calculate ETr, ETc can be found by applying the crop coefficient as follows:

$$ETc = Kc*ETr$$

Major Models

The most recent major review and recommendations of the various ET models was done by Doorenbos and Pruitt (15). Their paper was published by the Food and Agriculture Organization of the United Nations. These men present four methods of estimating ET, with the criteria for selecting one being the available climatic data. These four methods, or some variation of them, are prominent in other reviews of ET prediction equations (8,36,80). Because of their popularity and apparent success in widespread application, it seems reasonable to conclude that one of these four methods should have priority when choosing a procedure for predicting ET.

Evaporation Pans

The most widely employed empirical method involves some form of pan, usually a "Class A" weather pan (10,24,97). In this procedure no measured climatic data is needed. While meteorological factors have similar influences on evaporation from free water and soil surfaces and on transpiration from plants, there are some major differences. These differences include the changing characteristices of the plant surface during the growing season, availability of water for evaporation, and differences in energy absorbtion characteristics (23,26,43).

With these types of complex relationships, the simplest approach is to correlate pan evaporation (Eo) with a reference crop (80). The estimated ETr is then related to crop ET using a crop coefficient in the manner described in the previous section. If the operator of the pan takes due care, accurate estimates of periods as short as 10 days are possible (8).

Blaney-Criddle Method

Blaney and Criddle (5) developed and modified an empirically determined relationship between the mean air temperature (T in ^{o}F) and percentage of the total annual daytime hours (p). Their main assumption is that ET varies directly with the sum of the products of these two factors, which they called the consumptive use factor (f). Thorthwaite

(83) also proposed a procedure for predicting ET, which has become quite well known, based on this assumption. By then applying f to an empirically determined crop consumptive use coefficient (K), the consumptive water requirement (CU) is established.

$$CU = K*f = K(p*T/100)$$

The Blaney-Criddle K factor is not the same as the more familiar crop coefficient (Kc). The K values are computed from the equation K =U/F, where U is the consumptive use of the crop in inches for the growing season and F is the sum of the monthly consumptive use factors for the growing season (i.e. the sum of the products of the mean monthly temperature and the monthly percentage of daylight hours of the year) (86). The K factor is highly dependent on the specific type of crop and the environmental conditions under which it is grown. This means values taken from other areas must be used with caution.

This procedure was originally intended to make estimates of seasonal consumptive use. It may give reasonable monthly estimates (36) but because it is normally based on mean monthly climatic values, estimating shorter intervals may produce great errors.

Because of this and other limitations, the Blaney-Criddle method has undergone numerous revisions in order to make it useful in estimating shorter periods. One of the most recent and widely circulated modifications was put forward by Doorenbos and Pruitt (15). By incorporating general levels of wind, humidity and sunshine they reduced the need for local calibration. They also related this equation to a reference crop of grass. In addition to these changes the Blaney-Criddle K factor was dropped because of wide differences in the values presented in the literature.

The equation is:

$$ETr = c(p(0.46T + 8)) \text{ mm/day}$$

where ETr is the reference crop ET in mm/day for the period being considered; p is the mean daily percentage of total annual daytime hours for a given period and latitude; and c is an adjustment factor which depends on minimum relative humidity, sunshine hours and daytime wind estimates.

Though this equation solves for ETr in mm/day, the recommended estimation period is no shorter than 10 days (8). Discretion must be excercised when making estimates and this procedure should only be used when temperature is the only measured climatic data available.

Radiation Method

When measured sunshine, cloudiness or radiation are available along with temperature, some form of radiation procedure is recommended (15). Jensen and Haise (37) proposed a popular method similar to that which is presented in the FAO paper (15). The FAO equation is:

$$ETr = c(W*Rs) \text{ mm/day}$$

where ETr is reference crop ET in mm/day for the period being considered; Rs is solar radiation in equivalent evaporation in mm/day; W is a weighting factor which depends on mean humidity and daytime wind conditions. The radiation method should be more accurate than the Blaney-Criddle method, particularly at low latitudes, high altitudes and on small islands (15).

While it is possible to estimate solar radiation, it is highly desirable to have actual measurements for the period in question. The radiation method should not be employed to estimate ET rates for time intervals of less than 5 days (8).

Penman Method

The Penman equation (57), in principle, is a theoretical model. It requires measurements of temperature, humidity, wind and sunshine duration or radiation. The more of these factors which must be estimated due to lack of measurements the more empirical the equation becomes. By combining an energy balance equation with an empirical aerodynamic term, Penman was able to predict evaporation (Eo) from a free water surface. He could then relate this to potential ET of a full cover of short grass by means of an experimentally determined coefficient. This equation has been subject to some modifications but still remains reasonable intact.

One common modification is to relate the equation to a reference crop ET instead of Eo. Doorenbos and Pruitt (15) used grass as their reference crop giving the equation:

$$ETr = c(\frac{\Delta}{\Delta+\gamma}*Rn+(\frac{\gamma}{\Delta+\gamma})*f(u)*(ea-ed)) \text{ mm/day}$$

where ETr is reference crop ET in mm/day; Δ is the slope of the vapor pressure-temperature curve in millibars/^{o}C; γ is the psycrometer constant in millibars/^{o}C; Rn is net radiation in equivalent evaporation in mm/day; f(u) is a wind related function; (ea-ed) is the difference between the saturation vapor pressure at mean air temperature and the mean actual vapor pressure of the air, both in millibars; and c is an adjustment factor to compensate for the effect of day and night weather conditions.

For a more detailed explanation of the mechanics of the equation see the above reference. If all the measured data is available this equation gives a reliable estimate for periods as short as 1 day (8).

Soil Water Holding Characteristics

Information regarding the loss of water from the soil, by itself, is not sufficient to effectively schedule irrigation water. The water loss data must be coupled with information concerning the water holding characteristics of the soil and crop response to different levels of soil moisture depletion. It is important to know how much water a particular soil will "hold" and how much of this water can be lost without adversely effecting the crop (61).

Texture and Structure

The soil characteristic having the greatest bearing on the water holding capacity is the particle size distribution, commonly known as texture. The greater the percentage of silt and clay size particles in a soil the greater will be the water holding capacity. This is due to the direct relationship between particle size and specific surface. An increase in the percentage of fine particles will result in an increase in the specific surface. Because of the adhesive properties of water, the greater the specific surface, the greater the amount of water a soil will hold.

A secondary yet significant soil property which effects the water holding capacity is the structure. Structure is the term which describes the association of the discrete soil particles. The character of this association determines the pore size distribution. This distribution largely controls the rate of water movement in the soil. A soil with good structure will be well aggregated and have a broad distribution of pore sizes which permits the necessary soil drainage and aeration. Regarding these two properties, soil structure is more important than texture.

Organic matter is a soil constituent of great importance to structure. Colloidal organic matter is a prime factor in binding mineral particles into aggregates. The organic fraction can also hold a great deal of water relative to its mass.

Moisture Characteristic Curves

The water holding characteristics of a soil have usually been presented in one of two ways. The older of the two ways is a drainage curve. This plots percent moisture against time, showing the decreasing moisture content after a rain or irrigation. The second approach, which has become more common, is a moisture release (or retention) curve. This plots percent moisture against soil moisture tension. In the field, these two plots are essentially the same. As the soil drains over time the hydraulic conductivity decreases and soil moisture tension increases.

At the low tension end of the moisture release curve the effect of soil structure is most evident. This is because the large pores, which are most influenced by structure, will drain first. At higher tensions, the shape of the curve is dictated almost entirely by the specific surface of the soil, that is, the texture. These points again emphasize that the water holding properties of a soil are dominated by these two characteristics.

Hysteresis

The relationship between moisture content and soil moisture tension is not as precise as the experimentally determined curves might suggest. Soil moisture can arrive at a given tension from two directions, that is wetting or drying. Because of a phenomenon known as hysteresis the soil will have a greater moisture content at a specific tension during the drying cycle. Among the possible reasons (29) for this are:

1) The highly irregular pore spaces in the soil give rise to the "ink bottle" effect. Water capillarity causes this. Generally the narrowest constriction of a pore will control drainage while the widest portion of the pore will control filling. This means that at a given tension (or suction) value fewer pores will have drained during drying than will have filled during wetting. Because of this, hysteresis is generally greater in coarse textured soils where there are many large pores.

2) The contact angle of an advancing moisture front is greater, and therefore the radius of curvature is greater, than that of a receding front. This produces a water content having a greater suction value during drying than wetting.

3) The entrapment of air in pore spaces during wetting contributes to a lower moisture content in newly wetted soil.

The soil moisture release curves most often presented in the literature are of desorption. This is mainly due to the great difficulty of producing an accurate soption curve.

The use of tensiometers with these curves to schedule irrigation water is one obvious area where the hysteresis effects would be of importance. Even though hysteresis is known to be significant it is usually disregarded in practice (29,63). This disregard is because of the difficulties of quantifying the wetting curve, or of even knowing where a soil is in the wetting and drying cycle.

Available Water

The term "available water" describes a central concept in traditional thinking regarding irrigation scheduling. In a broad sense, this refers to water that is available for plant uptake. The availability is both in terms of potential energy and location.

As the soil dries, the remaining water is bound more tightly to the soil particles. This lowers the potential energy of the water. If this potential energy gets too low the plant is unable to extract the water and it is therefore unavailable. Some of the soil water may simply drain below the rooting depth of the plant. This water is likewise unavailable.

In common use, a quantity is associated with available water. This quantity may be expressed in any units, such as percent by weight or volume, millimeters per centimeter, or centimeters per meter. The upper and lower bounderies of available water are defined by the terms "field capacity" and "permanent wilting point". Both terms have been subject to much debate as to their validity. The utility of the bounderies they attempt to describe seem more responsible for their survival than their accuracy. It has been said of field capacity that if it "did not exist, someone would have to invent it" (30).

Field Capacity

In 1931 Veihmeyer and Hendrickson (90) coined the term field capacity to decribe "the amount of water held in the soil after excess gravitational water has drained away and after the rate of downward movement of water has materially decreased, which usually takes place within 2 or 3 days in pervious soils of uniform structure and texture." In spite of the subjective nature and the specific limitations of this definition (how many soils are of "uniform structure and texture" through the profile?), field capacity came to be accepted as an actual physical constant of each soil (30). The foundational assumption of this constant is that drainage becomes negligable after a few days.

Field capacity is usually determined by "periodic sampling of a wetted soil that is kept covered to prevent evaporation" (47). From the resulting drainage curve, the moisture content where the flow becomes "negligable" is designated as the field capacity. Some have attempted to broaden and simplify this concept by setting it in terms of the potential energy of the remaining water. The values -0.10 and -0.33 bar have both been put forward as possible energies for field capacity moisture potential (30,75).

The original concept of field capacity may approach reality in coarse textured soils (30). The rapid initial drainage of these soils, with the accompanying decrease in hydraulic conductivity, results in a sharp reduction in the subsequent drainage rate. This can be misleading though, for it has been shown that even in coarse textured soils drainage will continue at a significant rate for many days after wetting (30,46,93,95). These observations along with more recent studies of unsaturated flow processes (30) indicate that field capacity, however defined, is arbitrary in nature and not an intrinsic soil constant.

At the International Congress of Soil Science in 1960, L.A. Richards stated that in regards to the general understanding of soil water, "the field capacity concept may have done more harm than good" (60). The fundamental error of Veihmeyer and Hendrickson's original definition is that it tries to describe in static terms what has proven to be a dynamic process. The survival of field capacity 22 years after Richard's observation may largely be due to coincidence.

Seldom if ever, is a bare "wetted soil covered to prevent evaporation" found in nature. In the field some plant cover is normally present. This is especially true where the concept of field capacity is applied to assess available water for irrigation. After a soil has been wetted there will obviously be consumptive use of this water by plants prior to the "excess gravitational water" draining away. Wilcox (96) and Miller and Aarstad (46) have clearly shown that this consumptive use will effect the amount of available water.

The upward movement of water due to ET slows the downward drainage rate (94). At high rates of ET, plants can obtain substantial amounts of water that otherwise would be lost to deep drainage. Evapotranspiration may increase the conventional estimate of available water by as much as 40% of the ET that occurs between wetting and sampling (46). This increase is generally greater for sand than for finer textured soils (48). Under "usual summer environmental conditions" ET will reduce deep drainage enough to allow reasonable estimates of actual available moisture from conventional field capacity values (47). This interaction between ET and drainage is probably the reason field capacity has been a useful value over the years. These observations should also serve as a warning that when ET rates are low, neglecting the deep drainage losses may result in a serious overestimation of available water (47,49).

It is evident from the effect of ET rates on the validity of field capacity values that anything impinging on the redistribution of moisture in the profile will effect the field capacity (30). There are many factors that will be significant, among them are the following:

1) Soil texture and structure are central in determining the field capacity value. Soils with fine textures will have a less stable and less distinct value than those with coarse textures. Fine textured soils also take much longer to arrive at what may be considered field capacity. The type of clay and percentage of organic matter are important in this regard. Expanding clays and organic matter both retain very high amounts of water, causing soils with apparently similar textures to have different values for field capacity.

2)The depth of wetting and the antecedent moisture is also a factor. Generally, the more moisture initially present in the soil profile, the slower will be the redistribution. This will result in a higher value for the apparent field capacity.

3) Any layer in the profile which impedes the downward movement of water, such as clay, coarse sand or gravel, will increase the apparent field capacity of the soil above. This is because the impeding layer will largely control the rate of moisture redistribution in the soil.

Due to its fortuitous usefulness and for lack of any similar value which has a sounder theoretical base, field capacity is still widely used today. The above considerations should produce a degree of caution and a striving to make the field capacity estimates as meaningful as possible.

Permanent Wilting Percentage

The permanent wilting percentage (pwp) defines the lower boundary of the traditional available water. The determination procedure for pwp usually involves dwarf sunflowers (*Helianthus annus*) (62). The first step is to grow these plants in pots containing the soil type of interest. When the first pair of true leaves has developed, the soil is covered and the plants allowed to wilt. The pwp is defined as the highest soil moisture content at which the plant wilts and then will not revive when placed in a dark humid chamber (59,61). The pwp of a soil determined in this way has been shown to correlate well with the soil moisture content at 15 bars tension (41,61). Because of the ease and speed of determination, the 15 bar percentage is now commonly used as the lower limit of available moisture.

As was the case with field capacity, for a time, pwp was thought to be an intrinsic soil property. This idea, along with the notion that from field capacity to pwp the water is equally available for plant uptake, has been disproven (13,19,30,44,59,76). It too is simplistic to assign a specific soil moisture value to represent a permanent wilting point. The interaction between the soil-plant-atmosphere system is highly complex and there are many circumstances which could combine to produce permanent wilting in a plant. Climate and physiology define a plant's need for water while, generally, the unsaturated hydraulic conductivity function limits the ability of the soil to supply water to the roots. A soil moisture content that is adequate to meet a plant's needs under low transpirational demand may be insufficient if the demand suddenly becomes high (30). In addition, different plants have different abilities both in terms of extracting low potential water and in surviving low potential conditions (55).

The inadequacies of the pwp concept have led some people to abandon it altogether as a basis for irrigation management decisions (30). Another approach is the assessment, on a crop by crop basis, of plant sensitivity to moisture stress. The lower soil moisture boundary becomes the deficit (or potential) that results in significant yield reductions. In spite of the weaknesses and alternatives, pwp, like field capacity, is still widely used.

Potato Irrigation and Water Relations

The potato (Solanum tuberosum L.) has been the subject of numerous studies on ET and various aspects of crop water use (7,20,39,54,64,69,70,74,78,81,82). The need for informed water management is particularly great for potatoes because they are more sensitive to fluctuations in soil moisture than are most crops (11). In potato production, sensitivity generally translates into reductions in both yield and quality. Irrigation management studies on potatoes usually address three broad questions: i) when to irrigate in relation to soil moisture depletion; ii) what are the critical periods during the plants development when optimum moisture is essential to maintain yields; iii) what roles does moisture levels and timing play in tuber quality?

For many years the rule of thumb has been to irrigate before 50% of the available soil moisture has been depleted (6,11,58,67). This recommendation is still widely held today (17,65,91). The findings of a number of researchers, however, do not concur with this recommendation. Epstein and Grant (21) concluded that when soil moisture tension reached 0.25 bar the potato plant was experiencing stress. Hukkeri et. al. (32) got significant yield differences between plots irrigated at 0.3 and 0.5 bar tension and Jones and Johnson (38) found significant yield reductions between irrigating at 0.3 and 0.6 bar soil moisture tension. The above research would indicate that in some situations yield reducing stress may occur even before soil water drains to field capacity. This may account for the observation that even in years of seemingly adequate moisture, well timed supplemental irrigation can be beneficial (2). Once this early stress threshhold has been passed, some work indicates that there is a span of several bars of soil moisture tension at which no significant yield reductions occur (4).

While most data indicates that any moisture stress will result in a trend toward reduced yields, there are very clear periods during the physiological development of the potato when the adverse effects of stress are more pronounced (12,32,38,53,66). The most moisture sensitive stage in the potato's development appears to be that of stolon formation, elongation and tuber initiation (12,32,66). Early and late in the growing season, the potato is least effected by moisture stress.

The major issue surrounding tuber quality is marketability. This is largely determined by the size, shape and specific gravity of the potatoes. How moisture stress effects tuber quality is an area which is unclear. It is widely held that maintaining a high uniform level of soil moisture is the best environment for producing high quality potatoes (6,21,32,42). Tuber deformations are a serious problem among elongated potato varieties and all evidence points to moisture stress as being the prime cause of cracked and spindled potatoes (11,66). Knobby secondary growth on potatoes is likewise often attributed to significant fluctuations in soil moisture (21). Not all researchers have observed this relationship (11,40,66). They found factors such as number of stems per plant, soil temperature and complex seasonal interactions involved in producing secondary growth.

The effects of irrigation on the potatoes specific gravity has not always been consistent between different investigators. Some have observed an increase in specific gravity with increased moisture (6,11,34) while others have reported the opposite (56,67). Some have observed no differences in specific gravity due to different levels of soil moisture stress (34). These kind of contradictory observations indicate that the specific gravity of potatoes is determined by an interaction of factors rather than by moisture influences alone. Whatever the interactions may be on any aspect of potato yield and quality, the availability of moisture clearly plays a major role.

Line Source and Continuous Function Experimental Design

Fox (22) introduced a continuous variable experimental design which is becoming increasingly popular. In an experiment involving nitrogen fertilization of sweet corn he gradually increased the amount of nitrogen each plant received down the row. By incrementing in this way, border rows became unnecessary because the rate of increase was small and an increase of nitrogen in one direction was offset by a decrease in the other. The elimination of border rows will allow for more compact experimental plots. In addition, by varying a second factor at right angles to the first, a well defined crop response surface can be obtained.

Bauder et. al. (1) felt this design was worth pursuing. They made irrigation rate the second factor running perpendicular to nitrogen rate in corn. In order to get the continuous variable rate of water application, a trickle system was employed.

Hanks et. al. (28) simplified the variable application of water by means of a line source delivery system. Closely spaced risers on a single line running down the center of the plot produced the desired effect. The triangular shaped distribution pattern of the sprinkler heads gave a uniform application rate parallel to the line and continuously variable rates perpendicular to the line. Hanks feels that the best riser spacing will be a compromise between 4 factors (28):

1) Uniformity along the plot, which is optimal with sprinklers spaced at approximately 10% of the wetted diameter or closer, and reasonable for spacings up to approximately 20-25% of the wetted diameter.

2) Application rate and system flow rate, which vary inversely with the sprinkler spacing.

3) System cost, which increases as the sprinkler spacing decreases.

4) Compactness, to minimize the required end buffer zones.

The plot length can be increased by adding more risers but the plot width is limited by the wetted diameter of the sprinklers. Another limitation of this set-up is its susceptibility to wind. Even slight winds disrupt application uniformity. Selection of proper wind conditions during which to irrigate is important for success.

The statistical analysis of a continuous variable system is the most serious drawback (27). Because each treatment is necessarily surrounded by adjacent progressive treatments, randomization is not possible. The irrigation treatments are systematic rather than random. Without randomization there is no valid estimate of error for the irrigation main effect. Statistically significant statements can be made on other variables and their interaction with irrigation levels if they are randomized and replicated (28). Hundtoft and Wu (33) have done a detailed analysis of the statistics involved and concluded that when properly used the continuous variable design is a valuable research tool.

There apparently is an increasing willingness among some researchers to accept the uncertainty which accompanies this design in light of its potential usefulness. This attitude is seen by the increasing frequency with which the line source design is being used, particularly to assess the effects of differing irrigation levels (45,50,51,85).

As with the choice of a statistical confidence level, the seriousness of error must be weighed. It is important when analyzing this type of data to clearly acknowledge the uncertainty and to allow this uncertainty to accompany any conclusions drawn.

The statistical problems excepted, the line source design is ideal for studying the effects of different levels of irrigation. The triangular distribution pattern provides for maximum irrigation rates along the line source, with an increasing deficit moving away from the line at a right angle. This is why the design was chosen for this study.

MATERIALS AND METHODS

Location, Climate and Soil

This research was conducted in East Lansing at the Michigan State Soils Research Farm during the 1981 growing season. East Lansing is located in the north central portion of Ingham county between 42° and 43° latitude and 84° and 85° longitude. The climate of this area is temperate, receiving an annual average of 75.79 cm of rainfall and 100.08 cm of snow. About 61% or 46.23 cm of the rain comes between April and September. These months generally define the normal growing season. The average relative humidity at midafternoon is approximately 62% and in the summer months the area receives about 68% of the possible sunshine (87).

The soil of the experimental plot is predominately Metea loamy sand (Loamy, mixed, mesic Arenic Hapludalfs), with some minor intrusions of Spinks loamy sand (Sandy, mixed, mesic Psammentic Hapludalfs). These two soils are very similar. The major difference is that the Metea has a clay loam B2 horizon, commonly between 86 and 97 cm deep. Both soils are generally well-drained with good permiability. The permiability of the clay loam horizon in the Metea is moderate to slow (87). The reduced permiability of this layer will obviously modify the drainage rate of the entire profile.

Plot Layout and Preparation

A single irrigation line ran down the middle of the entire plot parallel to the rows. The plot was divided into three sections, ranges

I, II and III. Each of the ranges was 30.5 by 30.5 meters. A narrow alley was cut perpendicular to the rows completing the quartering of the range into 15.25 by 15.25 meter subsections. Each quarter was considered one replication. Each range was surrounded by a small border area of bare soil and the entire plot was bordered by mown grass (see fig. 1). The extended immediate environment included pasture to the west, corn to the north, dry beans to the east and soybeans to the south.

The line source set-up consisted of the single irrigation line with .61 meter risers at 3.05 meter intervals. The uniformities and relative rates of application were synthesized from single sprinkler catch data (see appendix A). These results were verified with rain gauges set in two rows perpendicular to the irrigation line.

The per hectar fertilizer rates were 170 kilograms of urea and 227 kilograms of 0-0-60 plowed down and 1136 kilograms of 16-16-16 banded at planting. The plot was then disked and certified seed tubers were planted at 25.4 cm spacings in .86 meter rows. Three potato varieties, Superior, Atlantic and Russet Burbank, were planted, with one variety in each range. Harvest rows were in pairs with a discard row on each side. The individual rows of each pair were treated as treatment subsamples within a replication. While the entire plot was uniform in terms of cultural practices (i.e. fertilization, cultivation, pesticides and irrigation), no comparisons were made between the varieties in the final analysis of the data. In this regard, each range was a separate experiment.

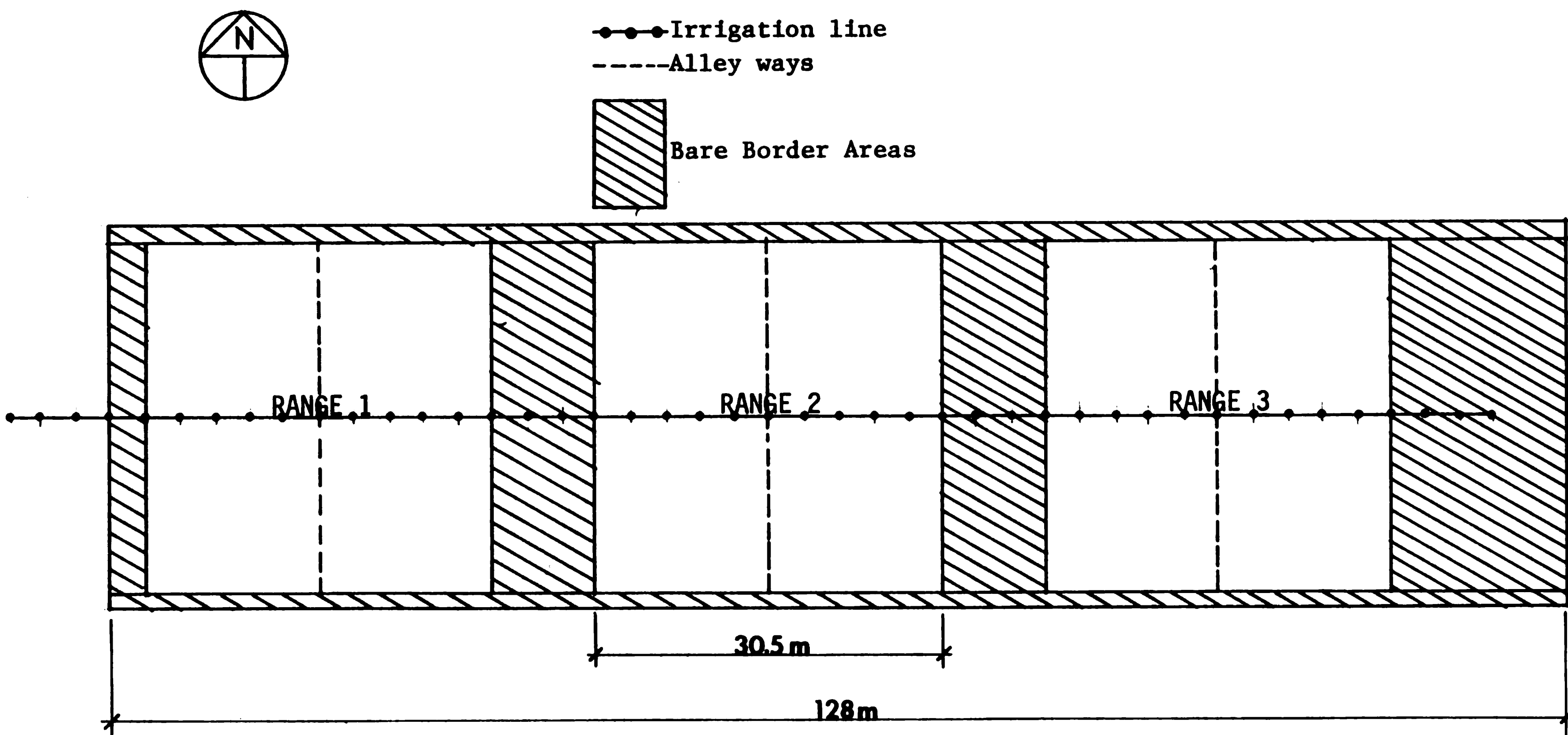

Fig. 1. Plot layout.

Soil Moisture Measurements

Tensiometers and a neutron probe were used to moniter soil moisture. The number and placement of tensiometers and access tubes was the same for all three ranges (see fig.2). Tensiometers were installed within the row at two depths, 23 and 46 centimeters (9 and 18 inches) and were read 3 times per week. The tensiometer readings were related to the volumetric moisture content with moisture release curves.

Ten soil cores, from each of 3 depths, were taken from each range according to the method outlined by Blake (3). The cores were soaked in water for at least 2 days so that they would be saturated. Upon removal from the vat of water, the cores were weighed and then placed in a pressure plate apparatus (59). The soil was subjected to 4 different pressures, 0.10 bar, 0.33 bar, 1.0 bar and 15 bars. When water was no longer moving out at a given pressure, the cores were again weighed and moved to the next higher pressure. After the 1.0 bar pressure was complete, the cores were dried at 104°C for 24 hours and then weighed. From this data the bulk densities of the soils were calculated. These bulk density determinations were used to convert from percent moisture by weight to percent moisture by volume. Disturbed samples were used instead of cores at the 15 bar pressure.

The soil moisture release curve is determined by plotting percent moisture by volume against the pressure. An equation can then be fit to the experimentally derived points. The equation which was used in this work was of the form:

$$y=a+b*\ln x$$

where y is percent moisture by volume; x is soil moisture tension in

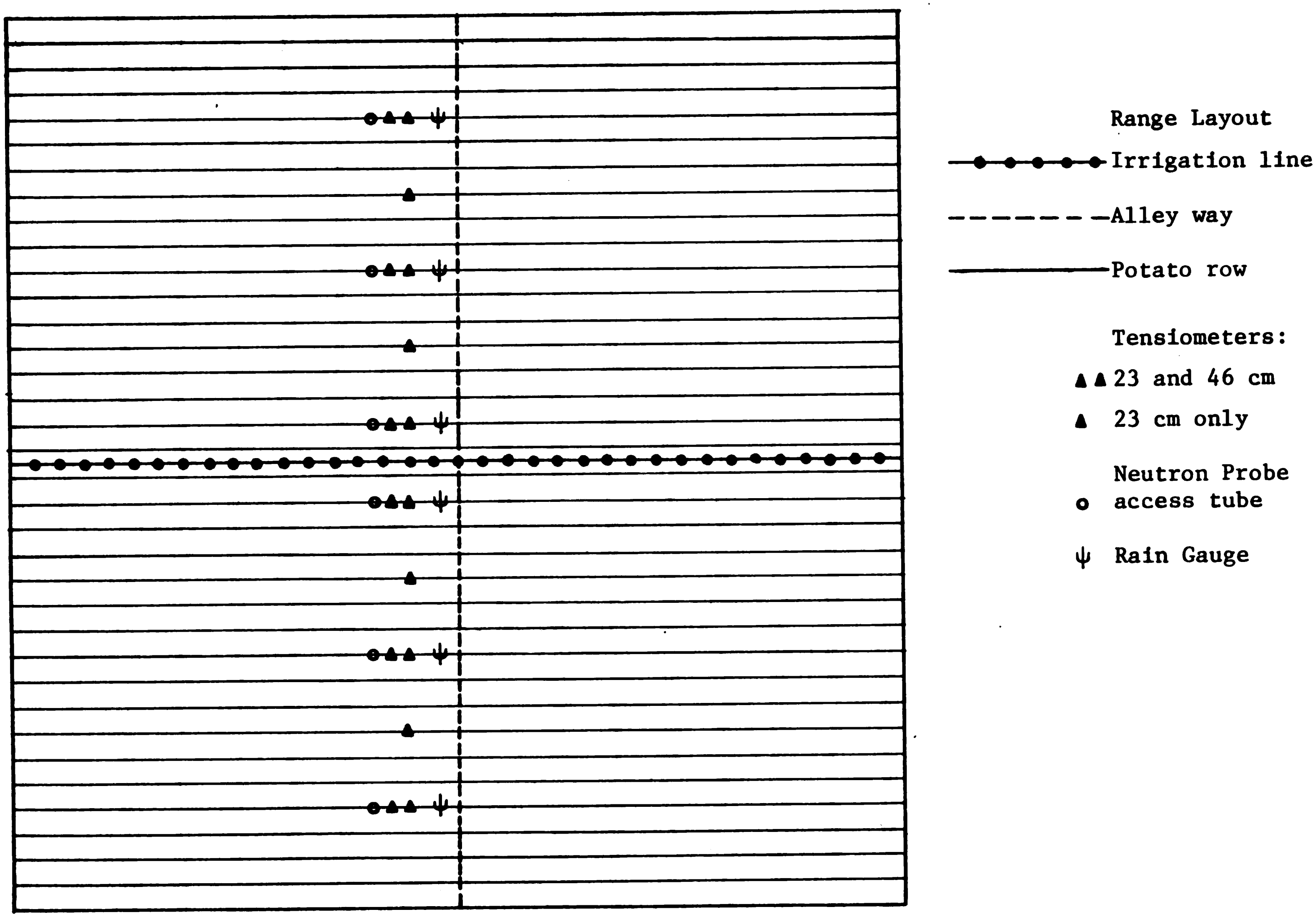

Fig. 2. Range Instrumentation.

centibars; and a and b are calculated coefficients. Figure 3 shows an example of one of these curves (the other curves are presented in appendix B). The x-axis range is only 0-1 bar. It was plotted in this way for several reasons. First, in the Metea loamy sand, the majority of available soil water is held between 0 and 1 bar tension. Also, the tensiometers will only read to about 85 centibars tension. Finally, to plot 0-15 bars would have sacrificed detail in the important 0-1 bar range with little gain in information.

Neutron probe access tubes were 91.4 cm long and like the tensiometers were installed in the row. Readings were taken beginning at 20.3 cm, then 30.5, 45.7, 70.0 and 76.2 cm (8,12,18,24 and 30 inches). Each tube was read on the same day, once per week. The instrument was a Troxler Nuclear Moisture Gauge, model 3222. The probe was used primairly to follow changes in soil moisture rather than absolute content. Because of this, it was decided to use the calibration curve determined by the manufacturer.

Water Management

Irrigation water was scheduled based on tensiometer readings. The water was applied in order to keep the average of the 12 tensiometers (4 in each range) nearest to the irrigation line below 50 centibars. In this study, the crop was irrigated only during morning and evening hours, when the wind was negligable. The amount was measured in rain gauges set at canopy height and considered 100% effective.

Rainfall and pan evaporation data was collected at the Soil Science Barn at Michigan State University. The rainfall plus the irrigation gave the estimate of moisture input to the soil. Changes in

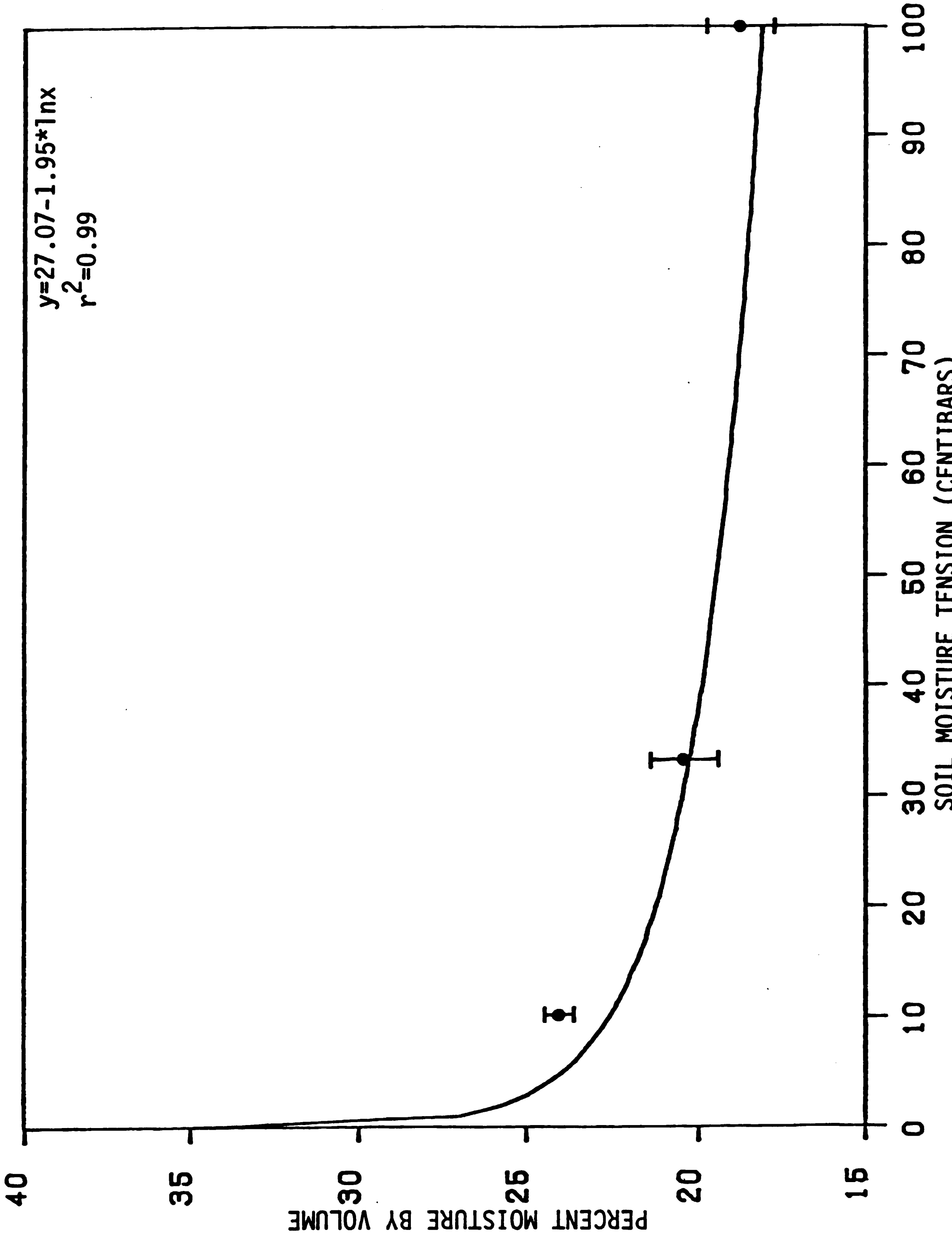

Fig. 3. Characteristic moisture release curve.

soil moisture content, as determined by the neutron probe, were taken to be the water losses. Using this data in a water balance, estimates of ET were obtained. These estimates were generally made for periods of one week, and then only when it was reasonably certain that the deep drainage losses were negligable. The form that this water balance equation took was:

$$ET=R+I-(SM_2-SM_1)$$

where SM_1 is the soil moisture content at time 1; SM_2 is the soil moisture content at time 2; R is the depth of rainfall that fell between time 1 and time 2; and R is the depth of irrigation that was applied between time 1 and time 2.

Yield and Quality Determinations

The digging of the potatoes was done mechanically when the particular variety was ready. Each harvest row of a pair was weighed separately. The weights of oversize, U.S. #1, undersize, and offtypes were all recorded. Specific gravity determinations were run on samples from each harvest row. Lastly, samples from each treatment were visually inspected with regards to internal quality.

RESULTS AND DISCUSSION

Soil Moisture Measurements

Figures 4-6 point toward the difficulty of arriving at precise values for soil moisture. These graphs compare the soil moisture values indicated by tensiometers with those from the neutron probe during a portion of the 1981 growing season. Appendix B presents the soil moisture release curves which relate soil moisture tension, measured by the tensiometers, to percent moisture by volume. The neutron probe is calibrated to indicate percent moisture by volume directly.

The variability between the two methods may be largely due to two factors. One, is the general trend of increasing soil moisture content with depth in the profile, to some maximum value. There are certainly circumstances where this will not be true. The most notable exceptions are where there are sharp textual changes, such as fine soil underlain by coarse textured soil, and where moisture fronts are moving through the profile due to recent rain or irrigation. With these instances excepted, the soil water content deeper in the profile will generally be less effected by evaporation and plant extraction. The second factor is the difference in the way the two instruments arrive at a soil moisture value. The tensiometer basically makes a point measurement of soil moisture. The value on the gauge corresponds to the moisture tension immediately adjacent to the ceramic cup. In contrast to this, neutron scattering averages the soil moisture of a larger volume of soil. A neutron probe reading, at 20 cms for example, will be an average moisture value of a sphere of soil reaching above and below the 20 cm depth. The volume of this sphere will increase with decreasing moisture

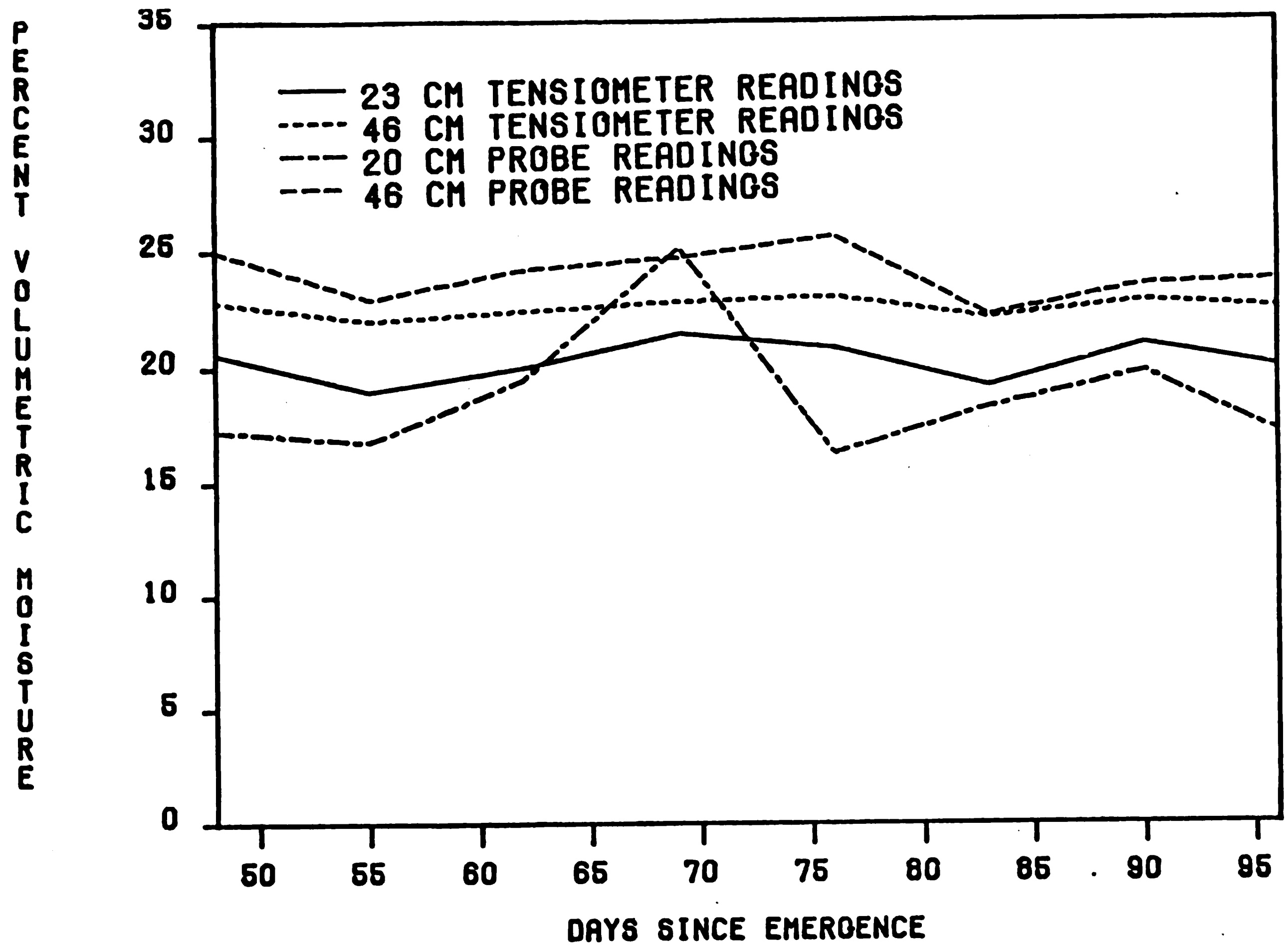

Fig. 4. Comparison between neutron probe and tensiometer readings in Range 1.

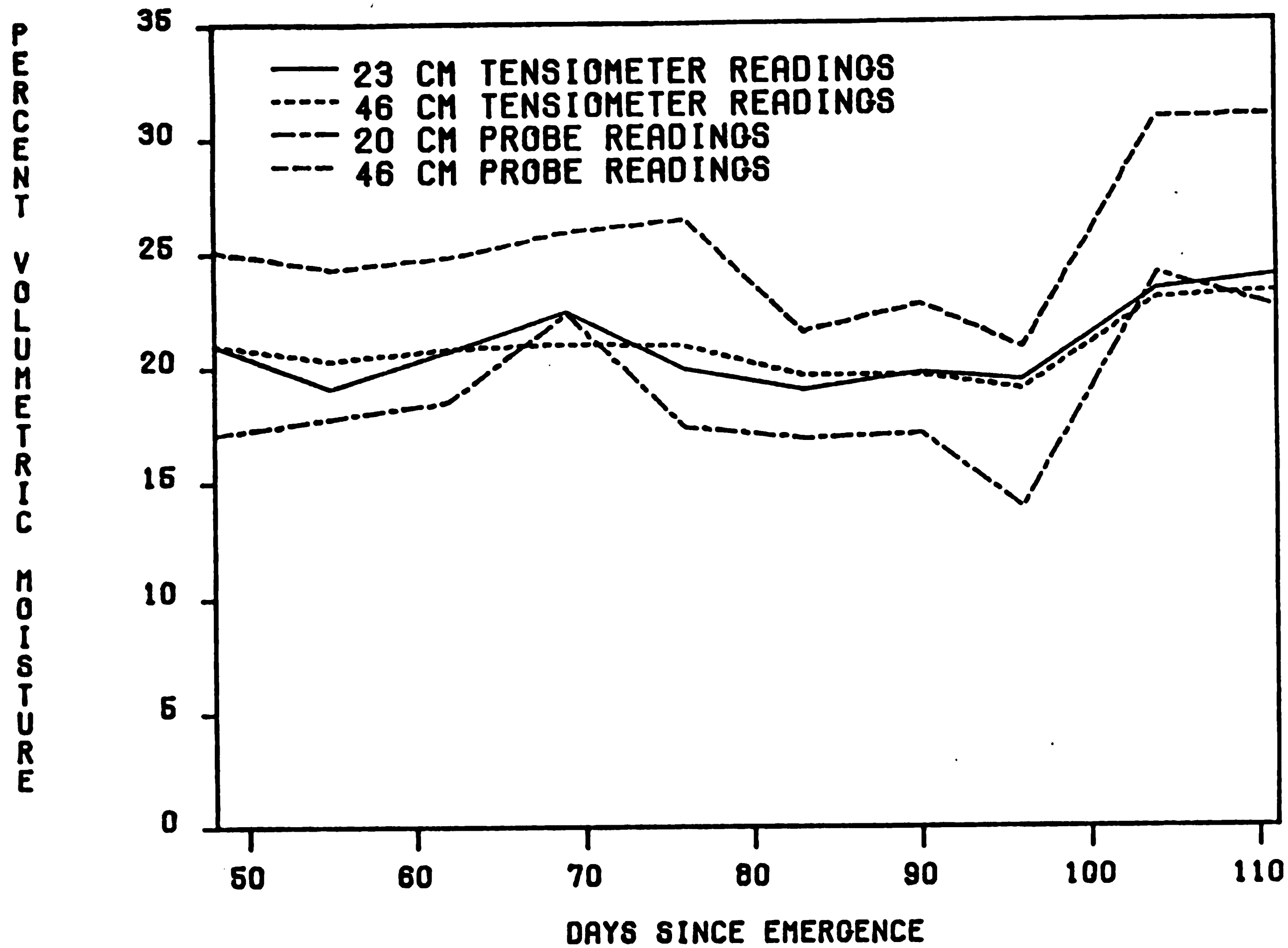

Fig. 5. Comparison between neutron probe and tensiometer readings in Range 2.

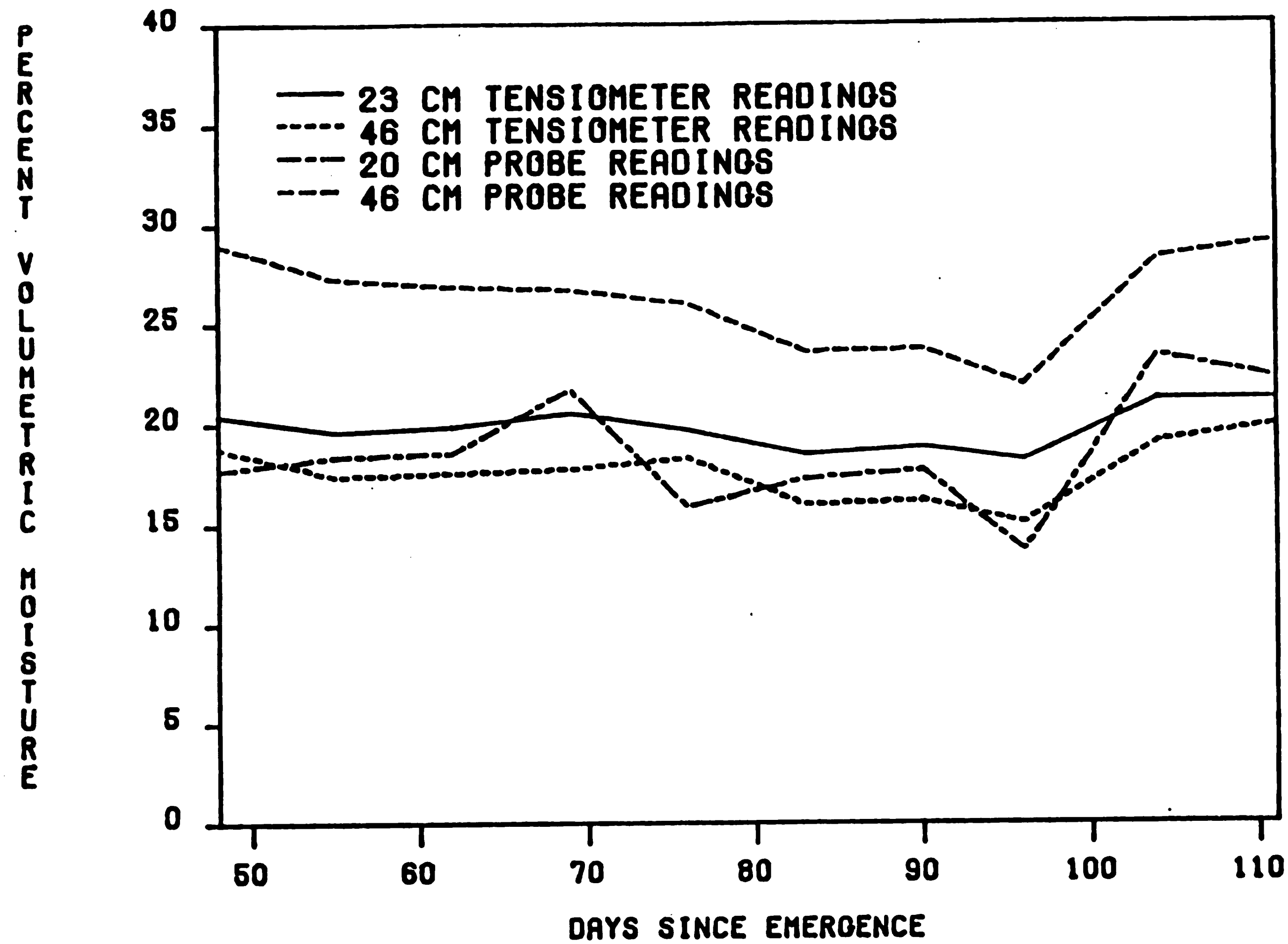

Fig. 6. Comparison between neutron probe and tensiometer readings in Range 3.

content. In wet soil, the radius of influence may be as small as 10 cm, while in dry soil it may be 25 cms and more (29). Barring wetting, the normal dryness of the surface of the soil due to evaporation, along with the possible loss of neutrons out of the surface of the soil, would be expected to result in a reading indicating that the soil is dryer than the actual moisture content at 20 cms. Therefore, the volume of soil considered and the changing water content through the profile will combine to influence the reading recorded by the probe for any given point.

This appears to be the kind of interaction involved in figures 4-6. The soil moisture contents indicated by the tensiometers at 23 and 46 cms run fairly consistently between the neutron probe values for 20 and 46 cms. By averaging the moisture values of the two depths for each instrument (figures 7-9) some of these changing moisture effects appear to cancel out. This may then be taken as the average moisture content for the first two feet and the two methods agree quite closely. By comparing the major deviations of these averaged values with the rain and irrigation records (appendix C), it is seen that the periods of large moisture inputs are also the periods of large deviations. This would indicate that the probe was sensing the presence of a moisture front which had not yet effected the reading on the tensiometer. The validity of this procedure is not tested beyond the data presented here. It may be worth some further investigation.

Range 3 probe readings (fig. 9) deviate more from the tensiometer readings than do the other two ranges. This disparity is clearly due to the difference between the 46 cm values for the two methods (see fig. 6). The patterns of changing moisture contents are very similar but the

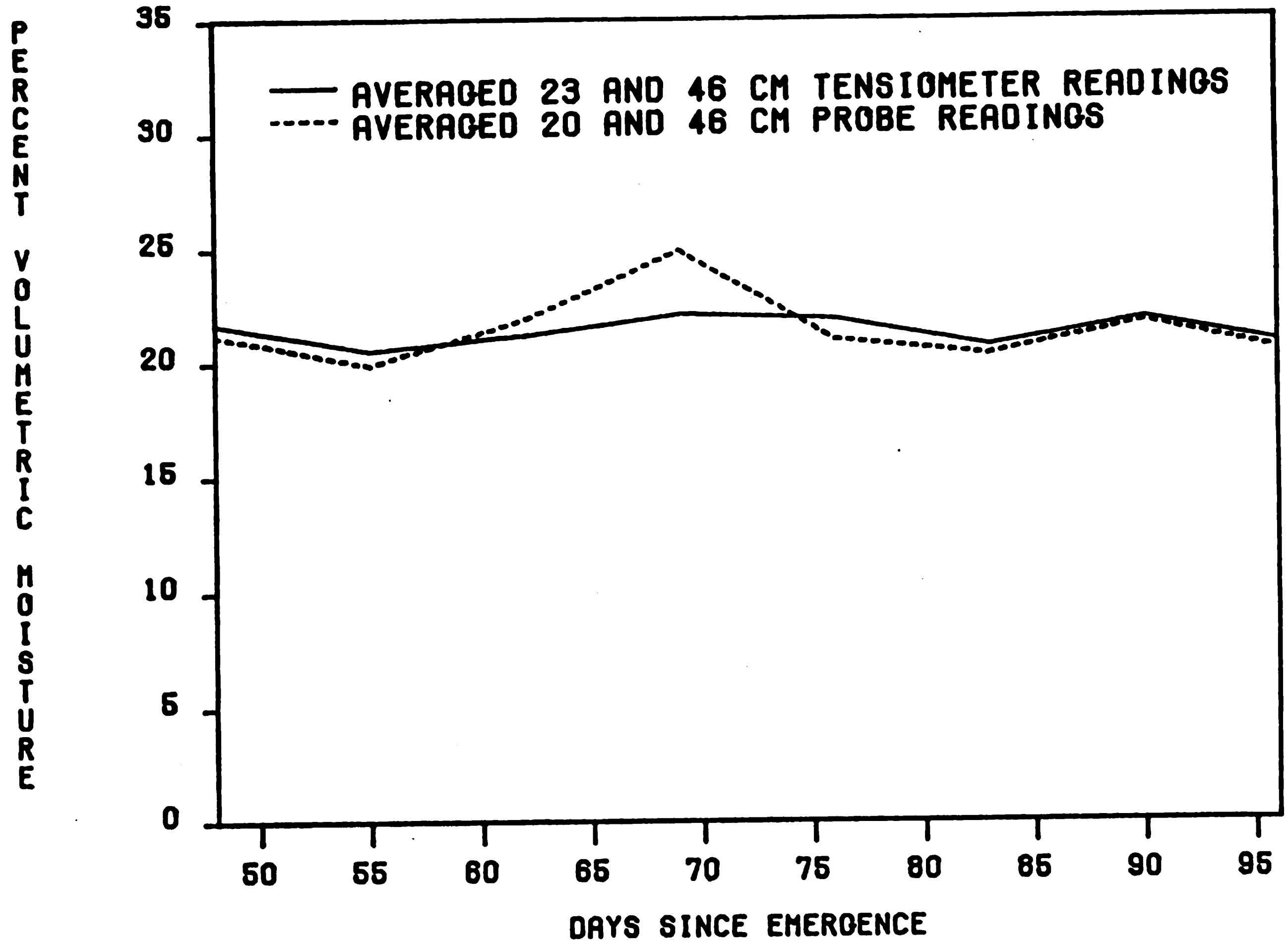

Fig. 7. Averaged neutron probe and tensiometer readings in Range 1.

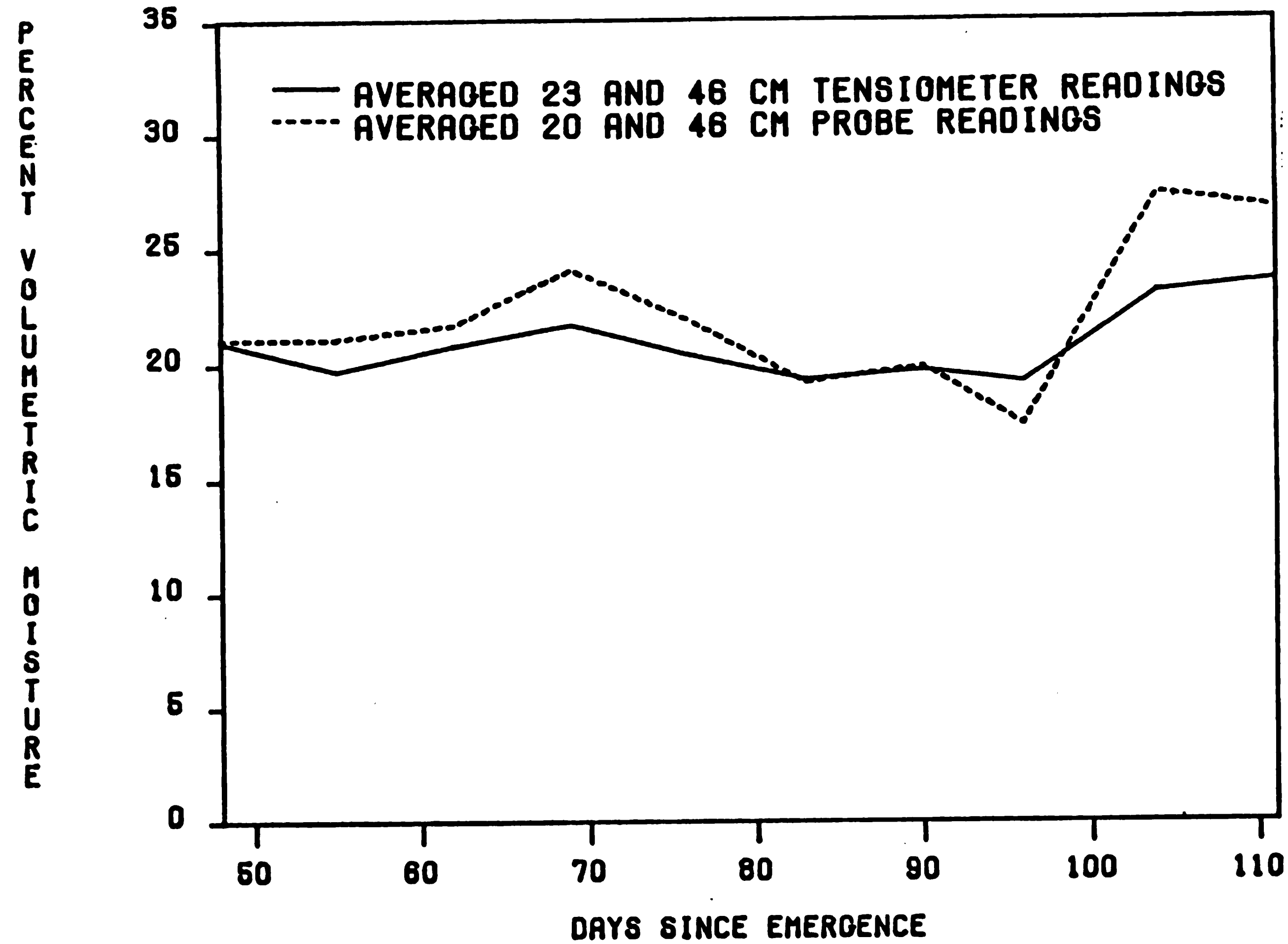

Fig. 8. Averaged neutron probe and tensiometer readings in Range 2.

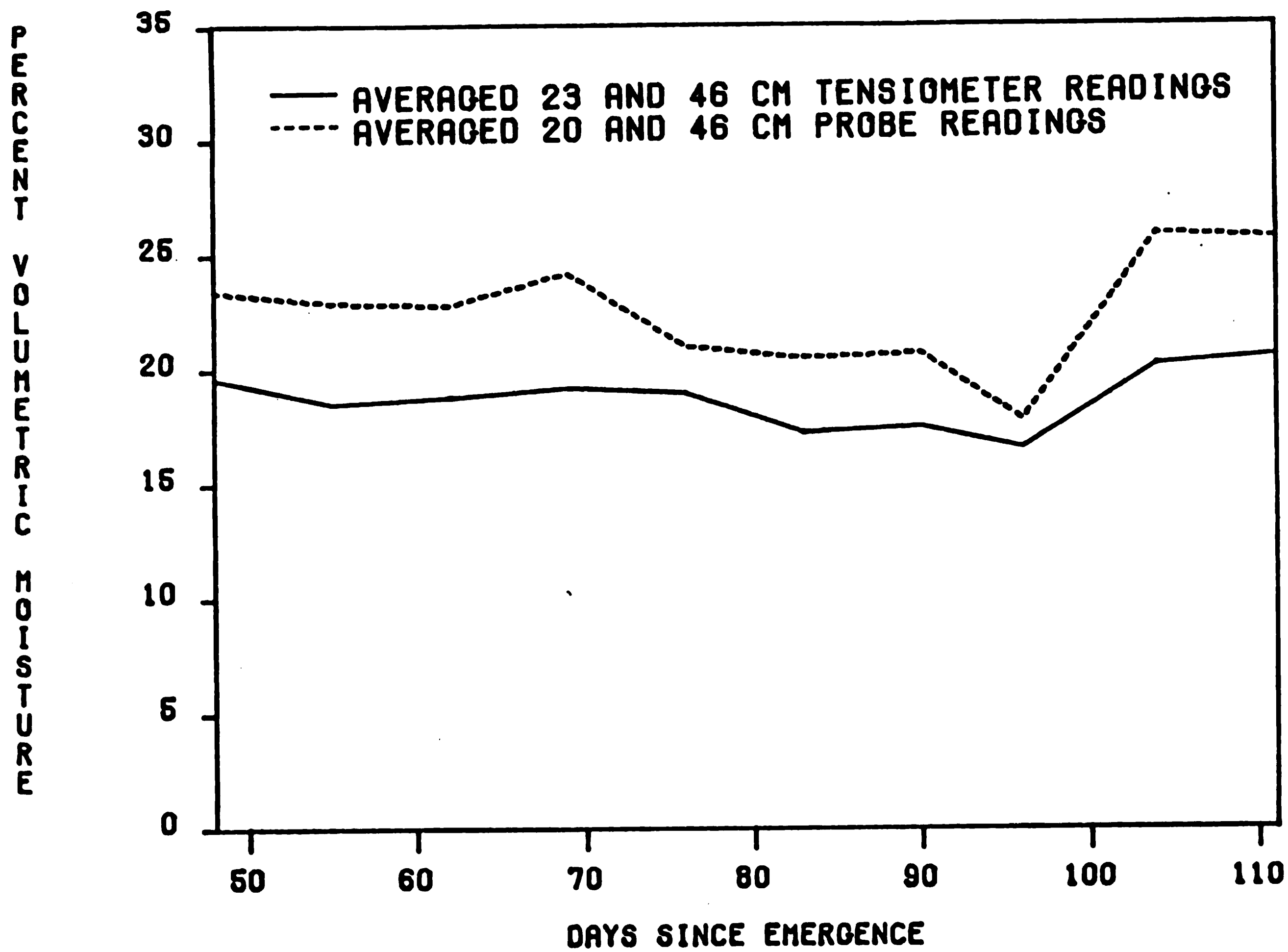

Fig. 9. Averaged neutron probe and tensiometer readings in Range 3.

probe consistently records about 8.5% more water than does the tensiometer. This difference translates to roughly 4% more water on the averaged values. These averaged values show a reasonable correspondence in the pattern of soil moisture changes.

The most likely explanation for these results is a nearby fine textured layer of soil which has a higher moisture holding capacity than the soil the tensiometer cup is set in. If this layer is close enough to influence the neutron probe readings, the result would be consistently higher estimates of the soil moisture for that depth.

When placing the particular access tube from which these readings were taken, the soil appeared to be Spinks loamy sand. This, as previously mentioned, is similar to the Metea but lacking the clay loam B2 horizon. Other soil samplings showed that there was Metea loamy sand very close to this tube. Because no soil samplings were taken immediatly around the access tube, the presence of a clay loam layer close enough to influence the probe cannot be confirmed. In spite of this, the kind of data shown here makes that presence very likely.

Water Balance Evapotranspiration Estimates

In this study the first 61 centimeters of soil, corresponding to the effective rooting depth of the potato, was taken to be the zone where water was lost due to ET. Changes in water below this zone were attributed to drainage. A time period was selected when water inputs were relatively low. This kept drainage losses negligible. In this case, negligible is when drainage losses are less than 10% of ET (30). During the 2 week period considered, these losses were well below this level.

Because of the volume of soil measured by the probe, it is possible to treat the data in different ways when assessing moisture losses. One approach is to calculate average values of soil moisture for intervals, for example 0-30 and 30-61 centimeters, and then to follow the changes in the moisture content of these intervals over time.

For this data, the 20 cm probe reading was taken as the best estimate of the first interval mentioned above. A weighted average was used for the second interval. The 45 cm value was weighted twice because its sphere of influence was entirely within the zone in question. The 30 and 61 cm readings were weighted once because they gave readings only partially derived from moisture within this interval. Soil moisture present above and below these depths is also averaged into the readings.

A second approach is to consider each reading down through the profile as the best estimate of the soil moisture for the interval immediately surrounding the depth of reading. In the present case, the 20 cm reading would then be the best estimate of the soil moisture from 0-23 centimeters; the 30 cm reading estimates 23-38 centimeters; the 46 cm reading estimates 38-53 centimeters; and the 61 cm reading estimates the average moisture content of the 53-61 cm interval. Once again the changes in the moisture content of these intervals are followed over time and the ET losses are computed.

Whichever way the data was treated, the estimate of ET was the same within significant digits. This being the case, only the averages of the soil moisture for 0-30 and 30-61 centimeters is presented here in tables 1-4. These tables show the ET calculations for each access tube in each range. The relative position of the tubes are shown in figure 3

Table 1. Range I evapotranspiration (centimeters).

Day of reading			SM	SM	SM_2-SM_1			
Date	DSE	TRT	0-30	30-61	0-30	30-61	R+I	ET/wk
7/6	48	1	5.28	7.92	----	-----	----	-----
7/13	55		5.13	7.26	-0.15	-0.66	3.30	4.11
7/20	62		5.94	7.59	+0.81	-0.33	4.29	3.15
8/3	76		4.98	7.90	----	-----	----	-----
8/10	83		5.59	7.01	+0.61	-0.89	1.50	1.78
8/17	90		6.05	7.47	+0.46	+0.46	2.29	3.20
8/23	96		5.23	7.42	-0.81	-0.05	1.27	2.13
7/6	48	3	5.79	7.72	----	-----	----	-----
7/13	55		5.03	6.76	-0.76	-0.97	2.24	3.96
7/20	62		5.31	6.71	+0.28	-0.05	3.00	2.77
8/3	76		5.82	7.62	----	-----	----	-----
8/10	83		5.44	6.81	-0.38	-0.81	1.32	2.51
8/17	90		5.64	6.88	+0.20	+0.08	1.85	1.57
8/23	96		4.93	6.71	-0.71	-0.18	0.84	1.73
7/6	48	5	2.62	6.25	----	-----	----	-----
7/13	55		1.96	5.36	-0.66	-0.89	0.13	1.68
7/20	62		1.93	5.05	-0.03	-0.30	0.48	0.81
8/3	76		2.62	5.21	----	-----	----	-----
8/10	83		2.72	5.05	+0.10	-0.15	0.99	1.04
8/17	90		2.74	5.13	+0.03	+0.08	1.02	0.91
8/23	96		2.18	5.05	-0.56	-0.08	0.00	0.64

Table 2. Range II evapotranspiration (centimeters).

Day of reading			SM	SM	SM_2-SM_1			
Date	DSE	TRT	0-30	30-61	0-30	30-61	R+I	ET/wk
7/6	48	1	5.21	7.92	----	-----	----	-----
7/13	55		5.44	7.57	+0.23	-0.20	3.30	3.28
7/20	62		5.64	7.75	+0.20	+0.18	4.29	3.91
8/3	76		5.28	8.08	----	-----	----	-----
8/10	83		5.16	6.83	-0.13	-1.24	1.50	2.87
8/17	90		5.21	7.11	+0.05	+0.28	2.29	1.96
8/23	96		4.24	6.55	-0.97	-0.56	1.27	2.79
7/6	48	3	2.92	5.99	----	-----	----	-----
7/13	55		2.46	5.92	-0.46	-0.08	2.24	2.77
7/20	62		2.54	5.28	+0.08	-0.64	3.00	3.56
8/3	76		2.67	5.51	----	-----	----	-----
8/10	83		2.84	4.98	+0.18	-0.53	1.32	1.68
8/17	90		2.87	5.16	+0.03	+0.18	1.85	1.65
8/23	96		2.34	4.93	-0.53	-0.23	0.84	1.60
7/6	48	5	3.05	6.07	----	-----	----	-----
7/13	55		2.46	5.26	-0.58	-0.81	0.13	1.52
7/20	62		2.13	4.88	-0.33	-0.38	0.48	1.19
8/3	76		3.07	5.00	----	-----	----	-----
8/10	83		3.07	4.85	0.00	-0.15	0.99	1.14
8/17	90		3.15	4.93	+0.08	+0.08	1.02	0.86
8/23	96		2.57	4.90	-0.58	-0.03	0.00	0.61

Table 3. Range III evapotranspiration (centimeters).

Day of reading			SM	SM	SM_2-SM_1			
Date	DSE	TRT	0-30	30-61	0-30	30-61	R+I	ET/wk
7/6	48	1	5.38	8.76	----	-----	----	-----
7/13	55		5.61	8.43	+0.23	-0.33	3.30	3.40
7/20	62		5.79	8.31	+0.18	-0.13	4.29	4.24
8/3	76		4.85	7.92	----	-----	----	-----
8/10	83		5.28	7.19	+0.43	-0.74	1.50	1.80
8/17	90		5.38	7.29	+0.10	+0.10	2.29	2.08
8/23	96		4.17	6.68	-1.22	-0.61	1.27	3.10
7/6	48	3	3.66	6.91	----	-----	----	-----
7/13	55		3.33	6.30	-0.33	-0.61	2.24	3.18
7/20	62		3.10	5.97	-0.23	-0.33	3.00	3.56
8/3	76		3.23	6.40	----	-----	----	-----
8/10	83		3.45	5.61	+0.28	-0.79	1.32	1.83
8/17	90		3.71	5.84	+0.25	+0.23	1.85	1.37
8/23	96		2.57	5.46	-1.14	-0.38	0.84	2.36
7/6	48	5	2.62	5.84	----	-----	----	-----
7/13	55		1.85	5.00	-0.76	-0.84	0.13	1.91
7/20	62		1.78	4.62	-0.08	-0.38	0.48	0.94
8/3	76		2.59	4.88	----	-----	----	-----
8/10	83		2.59	4.55	0.00	-0.33	0.99	1.07
8/17	90		2.44	4.47	-0.15	-0.08	1.02	1.24
8/23	96		2.01	4.32	-0.43	-0.15	0.00	0.58

Table 4. Average weekly evapotranspiration rates (centimeters).

Time period (DSE)	Measured ET TRT 1	TRT 2	TRT 3	Calculated ET
48-55	3.60**	3.30	1.70	4.47
55-62	3.77**	3.30	1.08	4.47
76-83	2.15**	2.01	1.08	4.14
83-90	2.41**	1.53	1.00	3.71
90-96	2.67N.S.	1.90	0.61	2.60

Significance levels were calculated using the t test and comparing the measured ET of treatment 1 with the calculated ET.

and are the same for each range. Tubes 3 and 4 received 100% of the possible irrigation water, tubes 2 and 5 got approximately 66%, and tubes 1 and 6 got no irrigation water during the growing season.

As was expected, the potato rows receiving the maximum amount of water had the highest ET rates. These rows do not estimate potential ET because the condition of never lacking water was not always satisfied. While the deficit was never great, the soil moisture tension was allowed to get up to 50 centibars and sometimes went slightly higher (see appendix D). As the water content in the soil decreases the remaining water is less available for plant uptake and the ET rates go down.

Maintaining the soil moisture tension below 50 centibars on coarse textured soil is probably the limit of most systems irrigating field crops in Michigan today. As was noted in the introduction, without supplemental rainfall there are often circumstances which do not allow irrigation to keep up with ET. This results in soil moisture tension considerably higher than 50 centibars during periods of drought. While these higher tensions do reduce the rate of water loss from ET, the rates still remain substantial. Even when the potatoes received 34% less water and the soil moisture tension was well beyond tensiometer range, the ET rates remained approximately 90% that of the maximum irrigation treatment. The rows receiving no irrigation water continued the trend of reduced ET. These rows lost water at about 35% that of the well-watered rows. The variation in ET rates at the various moisture levels is no greater between ranges than within each range. In light of this it is assumed that the varietal differences in ET rates are negligible during this part of the season.

Evapotranspiration Prediction Equation

The primary purpose of estimating ET losses in this study was to compare experimentally determined ET rates with those calculated from an empirical equation. This equation was developed by Dr. M.L. Vitosh at Michigan State University in 1981 and is used in an irrigation scheduling computer program.

In developing this equation, a linear regression was run on three factors, a consumptive use factor (x), a reference ET (ETo), and julian days (y). The consumptive use factor is similar to that in the Blaney-Criddle method where multiplying the mean daily air temperature (Tx) with the mean daily percent sunshine (P) gives x. Thirty year temperature means were used in the regression analysis while percent daily sunshine was obtained from a table of published values (86). The ETo values used in the regression were taken from calculations done by the Soil Conservation Service (92). They used long term weather data in the Penman equation to arrive at mean monthly ETo values for large geographical areas. When plotted on a map these values form lines which look similar to isotherm lines.

As an example, the regression gave the following equation for the East Lansing area:

$$ETo = 0.04864 + 0.01027x - .00034y$$

This equation has an r^2 of 0.995734. The only value measured during the actual use of this equation is mean daily air temperature. If daily measurements of P are available these should be used also but normally P is estimated from long term averages.

The crop ET (ETc) is found in the usual way:

$$ETc = Kc*ETo$$

The crop coefficient (Kc) is calculated by the methods outlined by Doorenbos and Pruitt (15).

The ET values which were calculated for the period measured experimentally are shown in table 4. When compared to the measured ET rates of the well-watered treatments it appears that the equation overestimates ET (fig. 10). Certainly caution must be exercised when judging the validity of this equation based upon 5 weeks of observations but an examination of the underlying assumptions and the application of this equation will reveal that an overestimation of ET was to be expected for periods shorter than one month.

With temperature being the only measured data in the equation, it must serve as the main factor determining the daily changes in energy available for ET. Because of this, the calculated ET will be the same for a given mean temperature whether rain falls all day or the crop receives 100% of the possible sunshine. If the mean daily percent sunshine was measured, this error would be greatly reduced. The monthly averages of P which are used, are reasonably constant from year to year but using them to estimate shorter periods can result in significant error.

It is possible that some error is contributed by the crop coefficients. The accuracy of these values may be effected by local environmental variations. Adjusting these coefficients to bring the calculated crop ET in line with the experimentally determined ET may improve the accuracy of this prediction equation. There is an obvious danger in doing this based on the results of this study. No evidence is

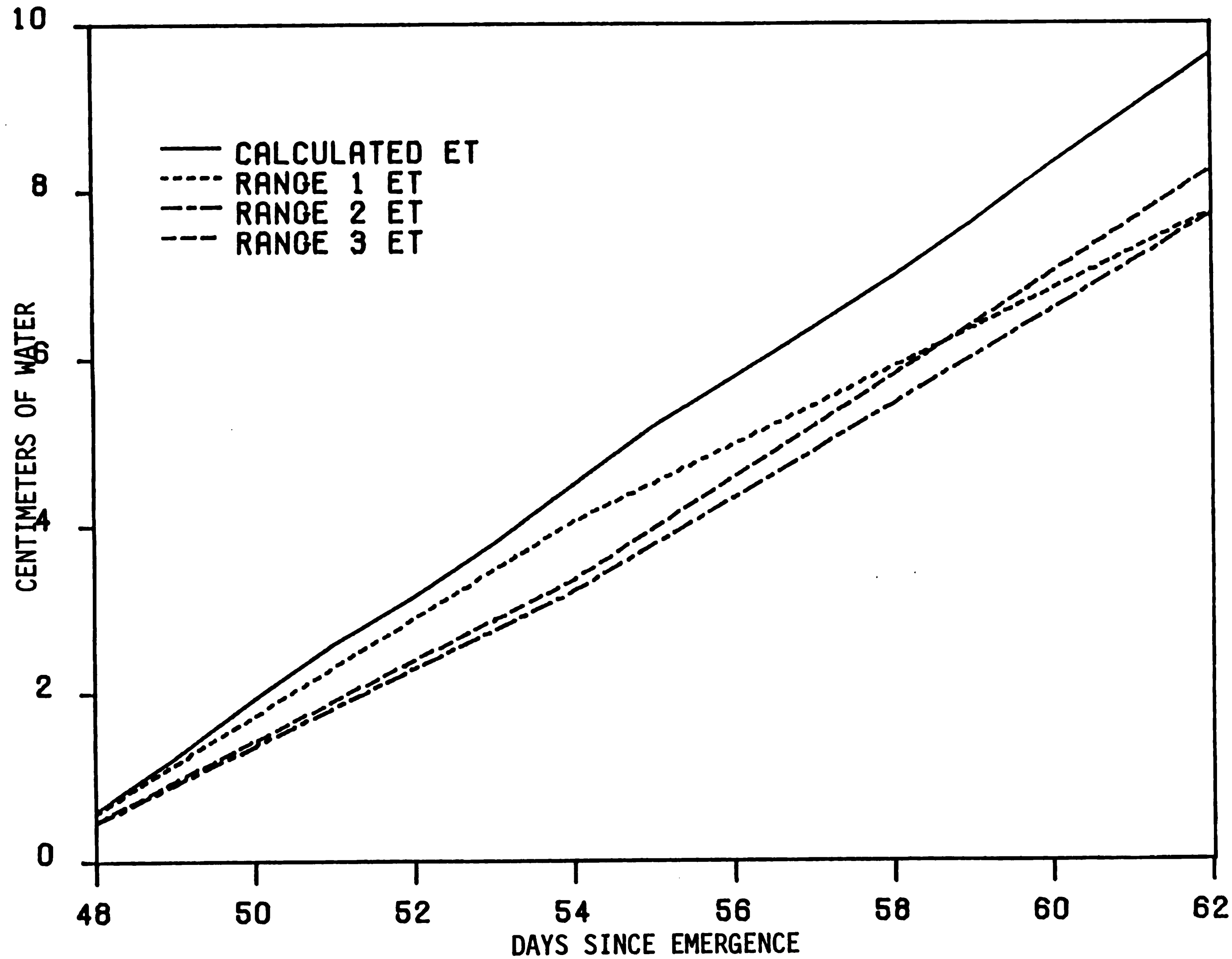

Fig. 10. Cumulative evapotranspiration, treatment 1.

presented here to specifically call the crop coefficients into question. Theoretically, it seems that the estimate of ETr itself is the major source of error. If this is true, a new crop coefficient will not improve the prediction of crop ET. In all likelyhood, an unjustified tampering with the established crop coefficients will result in greater errors.

Yield and Quality

Tables 5-7 report the yield and specific gravity results for the 3 potato varieties. The total yield is broken down into the 4 market catagories of U.S. #1, oversize, undersize and offtype.

Statistically these results were treated as a normal randomized complete block. It must again be emphasized here that because of the lack of randomization between the irrigation treatments inherent in the line source design, there can be no truly valid estimate of error. This does not invalidate the trends which are evident but it does call into question the levels of significance. Whatever conclusions are drawn from this data must be weighed in the light of this uncertainty.

Superior and Atlantic Varieties

Both of these varieties showed a smooth reduction in total yield as the amount of irrigation water decreased (see figures 11,12). Although the trend is clear, a reduction in irrigation water of over 2.5 cms in the Superiors and over 6.3 cms in the Atlantics was required before the yield losses became significant. This drop in yield was more pronounced in the Superior variety.

The irrigation treatments which are significantly different

Table 5. Yield results for the Superior variety.

TRT	Irrigation water %	(centimeters)	Over size	U.S. # 1	Under size	Total yield	Specific gravity
			--------quintals/hectar-------				
1	100	(15.75)	57.9	422.9	16.8	497.6	1.075
2	83	(12.95)	58.6	404.8	14.0	477.3	1.075
3	66	(10.41)	54.8	365.2	16.4	436.4	1.076
4	33	(5.08)	37.2	311.7	14.0	361.8	1.078
5	0	(0.00)	17.9	242.8	16.0	276.8	1.078
LSD(.05)			18.5	36.5	N.S.	44.6	N.S.

Table 6. Yield results for the Atlantic variety.

TRT	Irrigation water %	(centimeters)	Over size	U.S. # 1	Under size	Total yield	Specific gravity
			--------quintals/hectar-------				
1	100	(19.56)	108.2	428.1	26.8	563.0	1.091
2	83	(16.26)	108.6	398.6	23.5	530.8	1.092
3	66	(12.95)	108.6	395.7	23.2	527.5	1.089
4	33	(6.35)	93.6	340.6	23.3	457.5	1.086
5	0	(0.00)	66.1	306.3	21.5	421.9	1.089
LSD(.05)			24.1	35.8	4.7	45.9	N.S.

Table 7. Yield results for the Russet Burbank variety.

TRT	Irrigation water %	(centimeters)	Over size	U.S. # 1	Under size	Off type	Total yield	Specific gravity
			-----------quintals/hectar----------					
1	100	(19.56)	19.8	338.9	56.0	68.0	482.7	1.080
2	83	(16.26)	15.5	323.3	41.2	138.8	518.8	1.078
3	66	(12.95)	12.1	263.6	50.0	178.2	503.9	1.077
4	33	(6.35)	0.9	173.0	57.5	235.2	466.6	1.073
5	0	(0.00)	0.0	102.2	63.4	240.0	423.6	1.072
LSD(.05)			12.2	74.6	14.0	54.1	50.4	0.004

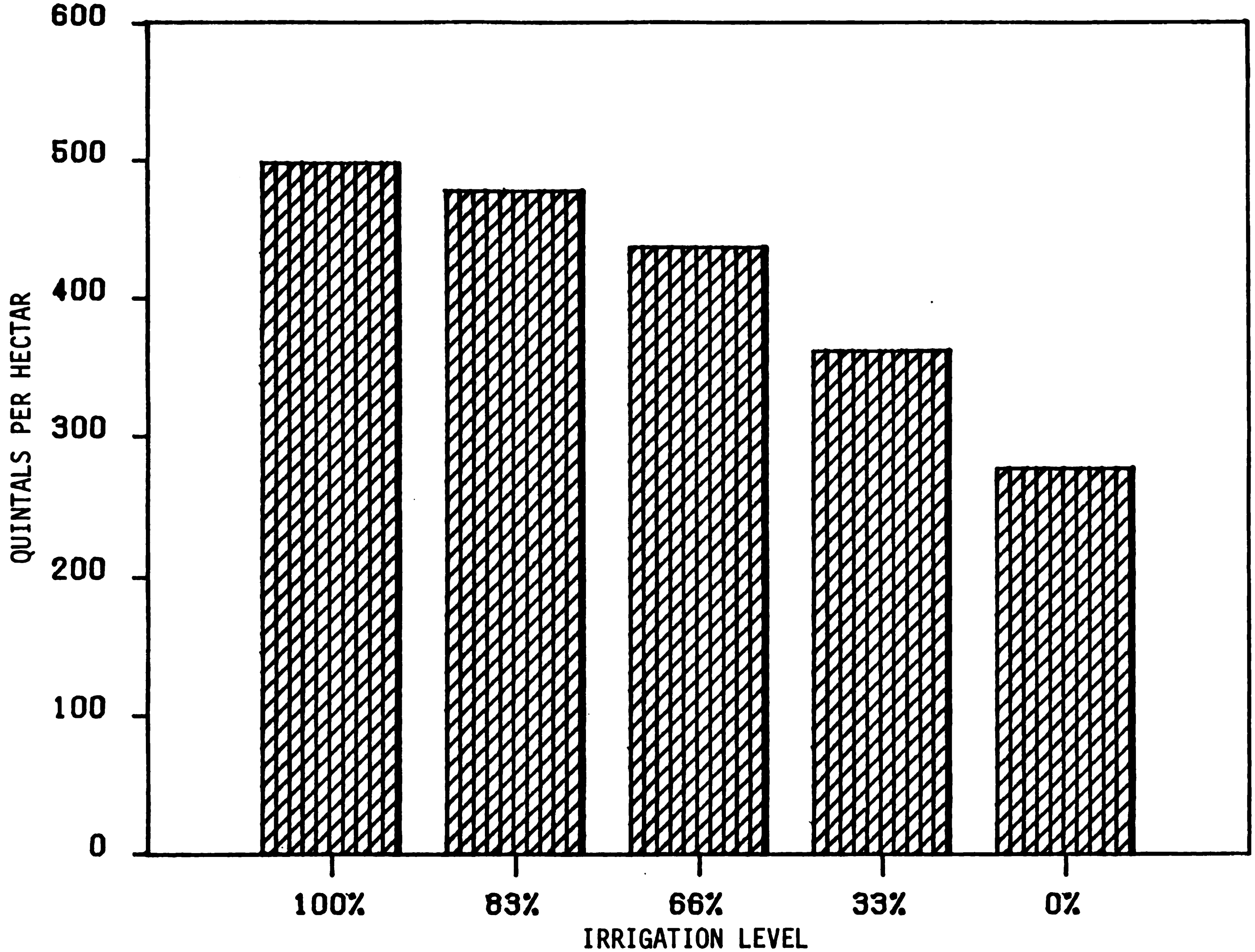

Fig. 11. Treatment comparisons of total yield for the Superior variety.

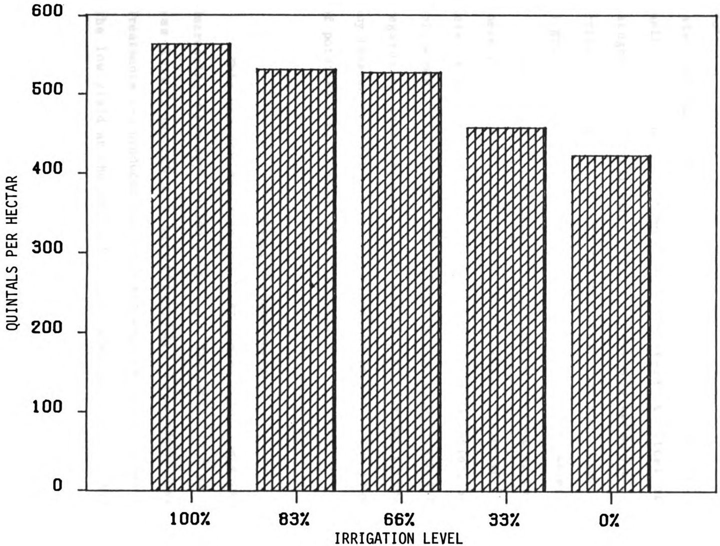

Fig. 12. Treatment comparisons of total yield for the Atlantic variety.

in terms of total yields are the same as those significantly different regarding U.S. #1s, with one minor exception. Reducing the amount of water applied to either variety has little, if any, effect on the quality of oversize potatoes. When the yield of either of these two categories did significantly differ it was only between the 100% and 0% irrigation levels. This data clearly shows that the yield of the U.S. #1 grade potato will be most effected by a shortage of water.

The level of irrigation had no apparent effect on the quality of these two varieties. The potatoes were visually inspected for internal defects such as internal necrosis, valcular darkening, brown center, hollow midrib and hollow heart. There was no significant difference in regards to internal quality or specific gravity for either variety in any treatment. Offtypes are not a quality factor in the round varieties of potatoes like Superior and Atlantics.

Russet Burbank Variety

This variety deviated from a step-wise total yield reduction with decreasing water application (fig. 13). The total yield of treatment 1 was lower, though not significantly, than treatments 2 and 3. Treatments 2-5 produced the yield pattern seen in the other 2 varieties. The low yield at the 100% irrigation level may have been due to a heavy early blight infection in this treatment in early August.

The undersize grade, with one exception in treatment 2, shows no significant yield differences. There is no ready explanation for this low undersize yield in treatment 2. Oversize Russet Burbanks seem to be quite sensitive to the amount of irrigation water received, going from 19.8 quintals per hectar in treatment 1, to 0 quintals per hectar in

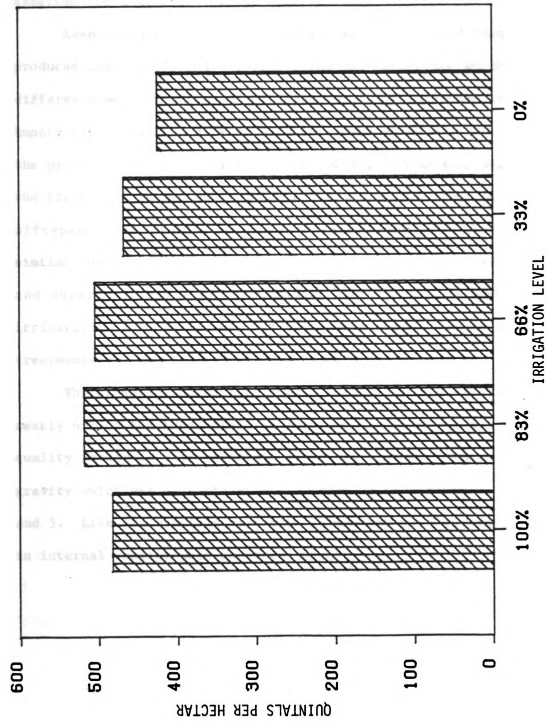

Fig. 13. Treatment comparisons of total yield for the Russet Burbank variety.

in treatment 5. Like the oversize, the U.S.#1 grade potato follow the expected trend of lower yields with less water.

Even though treatment 1 had a lower total yield than 2 and 3, it produced more U.S.#1 and oversize potatoes. The grade which made up the difference was the offtype. Offtypes, which in this case refers only to knobby tubers, adds a dimension to this data which was not present for the previous varieties. The yield of offtypes generally ran opposite to the trend seen in the other grades, that is, the less water the more offtypes. The treatments showing significant differences are very similar between offtypes and U.S.#1s. As was the case with Atlantics and Superiors, the U.S.#1 yields were hurt the most by any reduction in irrigation. Apparently, many of this grade became knobby in the dryer treatments.

The dramatic increase in knobby tubers, from 14% in treatment 1 to nearly 60% of the total yield in treatment 5, is certainly the largest quality factor in this variety. There was a steady drop in the specific gravity which was significant when comparing treatments 1 and 2 with 4 and 5. Like the previous varieties, there was no discernable difference in internal quality when assessed visually.

Summary and Conclusions

Evaluating soil moisture measurement techniques was not a central focus of this study, but the data is worthy of comment. Tensiometers, coupled with soil moisture release curves, compared very favorably with the neutron probe in assessing the profile soil moisture. Tensiometers placed at two depths, 23 and 46 centimeters in this case, provided satisfactory average estimates of the 0-61 centimeter moisture content. When making these calculations, moisture fronts and sharp textural changes within the profile must be taken into consideration. By knowing the characteristics of the particular soil type and monitoring the water inputs to the soil, allowances can be made for these two factors.

The ET prediction equation used in 1981 for the purpose of irrigation scheduling overestimates ET. It is unrealistic to expect an equation derived from mean monthly weather values and including only one measured variable to predict daily ET. Daily measurements of sunshine would greatly improve the sensitivity of the short term prediciton. The general unavailability of this data is the obvious problem. This study certainly points out that when making irrigation scheduling decisions, it is critical to have some type of soil moisture measurements, such as tensiometers, to verify any calculated ET values.

All 3 varieties responded to irrigation in 1981. Statistically, these responses in regard to total yield were not judged significant at P=.05 until there was a reduction of between 34% and 66% of the applied irrigation water, depending on the variety. Several other things did stand out in the data. In every variety, when total yields dropped, it was primarily the U.S.#1 grade from which these yield reductions came.

In the Russet Burbanks, when irrigation was reduced, the occurance of knobby tubers increased dramatically. Again, it was the U.S.#1 grade yields which were most effected by the increase in knobby tubers. This data would tend to support those in the literature who feel that knobby tubers are strongly related to the potato's water relations. Finally, irrigation level had no effect on the visible internal quality of any of the varieties. In the Superiors and Atlantics the specific gravity was likewise uneffected. Russet Burbanks did show a significant decrease in specific gravity with lower irrigation.

Recommendations

I. The literature concerning soil moisture management using tensiometers is weak. Further research in this area would be of value. The specific areas which might be addressed are:

A) How many tensiometers are needed to effectively schedule different size fields and different soil types and associations?

B) What are the optimum depths of placement for the tensiometers for various crops, soil types and soil conditions?

II. The present ET prediciton equation should be evaluated using daily measured percent daily sunshine to determine if this does in fact improve the short term accuracy of the calculated ET.

III. Some kind of concerted effort should be made to establish a wider network of stations to record daily measurements of the data that is required for accurate short term estimates of ET. This may only be feasible in areas where the ET prediuctions are of greatest value.

APPENDIX A

SPRINKLER DISTRIBUTION AND UNIFORMITY STUDY FOR THE LINE SOURCE EXPERIMENTAL DESIGN

Sprinkler Distribution and Uniformity Study for the Line Source Experimental Design

This study was undertaken to determine the actual distribution pattern and uniformity produced by the line source system. These two factors were determined for rows moving both perpendicular and parallel to the lateral line. Uniformities were calculated using Christiansen's equation (72).

The set-up of the system consisted of Rainbird #20 full circle impact sprinkler heads with .48 cm nozzles run at 40 psi. A sprinkler set-up, as described above, was run for several hours. Water was caught in cans set at 1.52 meter intervals running out in 4 different directions from the riser. This data was then synthesized into a distribution pattern along two lines (figures 1a and 2a). The wetted diameter of six sprinklers overlap to make the complete distribution pattern. Tables 1a and 2a show the contribution of each of the 6 sprinklers to any one point. Tables 3a and 4a show the uniformity calculations perpendicular and parallel to the lateral line.

This synthesized data was confirmed by rain gauge measurements taken in the plot during irrigation periods.

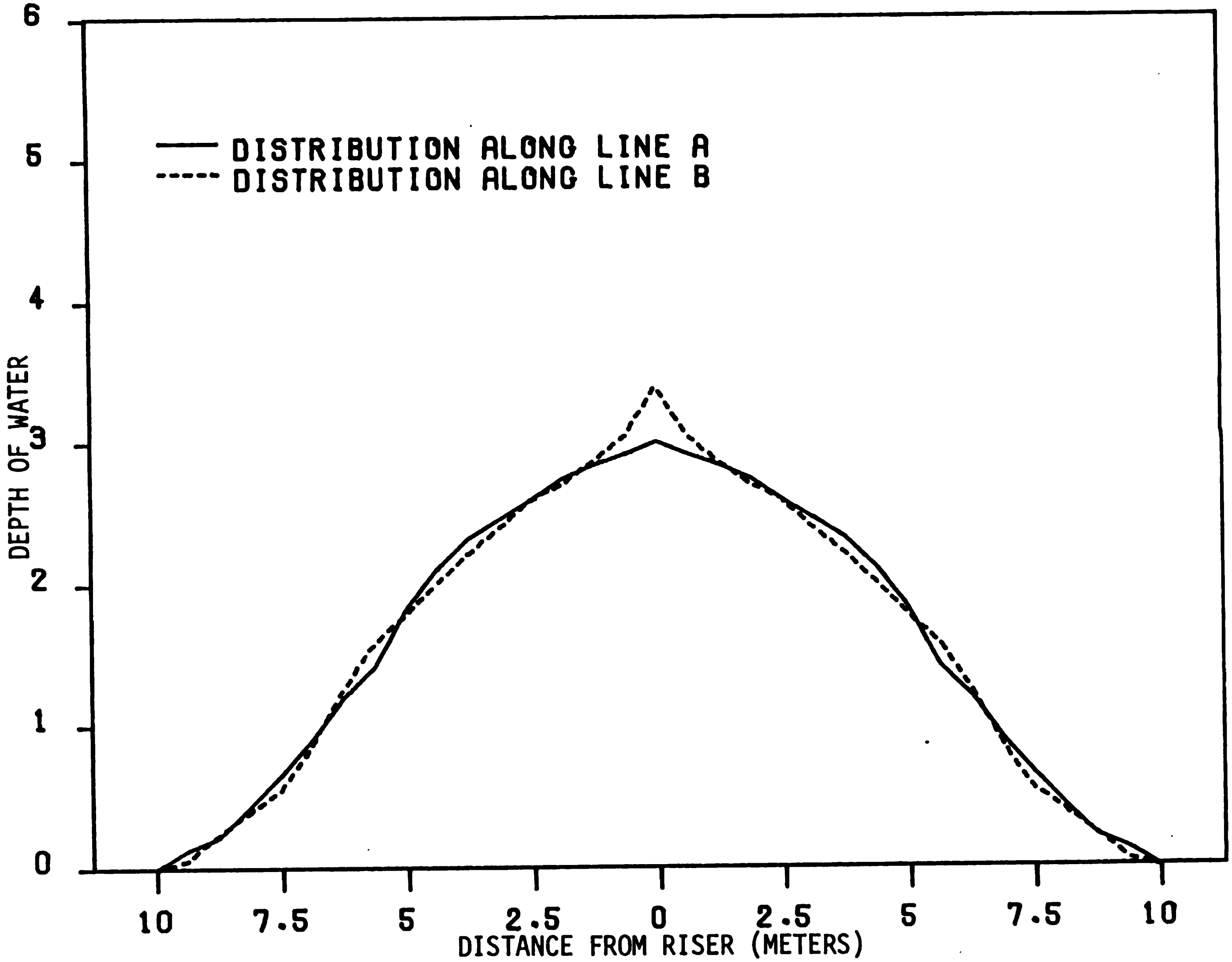

Fig. 2a. Distribution patterns along lines A and B; units of water are arbitrary.

Table 1a. Contribution by each sprinkler to each point.

Meters from riser	Along Line A 1	2	3	4	5	6	Total
0	.188	.563	.750	.750	.563	.188	3.00
0.61	.170	.550	.735	.735	.550	.170	2.91
1.22	.165	.540	.710	.710	.540	.165	2.83
1.83	.160	.530	.680	.680	.530	.160	2.74
2.44	.145	.510	.640	.640	.510	.145	2.59
3.05	.135	.490	.598	.598	.490	.135	2.45
3.66	.120	.450	.590	.590	.450	.120	2.32
4.27	.075	.410	.563	.563	.410	.075	2.10
4.88	.063	.326	.520	.520	.326	.063	1.82
5.49	0	.250	.465	.465	.250	0	1.41
6.10	0	.188	.410	.410	.188	0	1.20
6.71	0	.150	.300	.300	.150	0	0.90
7.32	0	.118	.210	.210	.118	0	0.66
7.92	0	.063	.150	.150	.063	0	0.43
8.53	0	0	.110	.110	0	0	0.22
9.14	0	0	.063	.063	0	0	0.12

Table 2a. Contribtuion by each sprinkler to each point.

Meters from riser	Along Line B 0	1	2	3	4	5	6	Total
0	.063	.438	.625	1.14	.625	.438	.063	3.39
0.61	0	.425	.623	.940	.623	.425	0	3.04
1.22	0	.410	.620	.800	.620	.410	0	2.86
1.83	0	.380	.612	.720	.612	.380	0	2.70
2.44	0	.360	.595	.675	.595	.360	0	2.59
3.05	0	.300	.580	.625	.580	.300	0	2.39
3.66	0	.250	.550	.605	.550	.250	0	2.21
4.27	0	.205	.505	.580	.505	.205	0	2.00
4.88	0	.160	.460	.540	.460	.160	0	1.78
5.49	0	.135	.410	.490	.410	.135	0	1.58
6.10	0	.105	.300	.438	.300	.105	0	1.25
6.71	0	.063	.210	.330	.210	.063	0	0.86
7.32	0	0	.160	.225	.160	0	0	0.55
7.92	0	0	.120	.160	.120	0	0	0.40
8.53	0	0	.063	.115	.063	0	0	0.24
9.14	0	0	0	.063	0	0	0	0.06

Table 3a. Uniformity moving out perpendicular to the line source.

Row	Row distance from line (meters)	Interval measured	Depth A	Depth B	Line A $\bar{y}$	Line A $\lvert\Delta\bar{y}\rvert$	Line A Uc%*	Line B $\bar{y}$	Line B $\lvert\Delta\bar{y}\rvert$	Line B Uc%
1	0.9	0.6-1.2	2.91 2.83	3.04 2.86	2.87	.04	98.6	2.95	.09	97.0
2	1.7	1.2-1.8	2.83 2.74	2.86 2.70	2.79	.05	98.4	2.78	.08	97.1
3	2.6	2.4-3.0	2.59 2.45	2.59 2.39	2.52	.07	97.2	2.65	.06	97.9
4	3.4	3.0-3.7	2.45 2.32	2.39 2.21	2.39	.07	97.3	2.30	.09	96.1
5	4.3	4.3-4.9	2.10 1.82	2.00 1.78	1.96	.14	92.9	1.89	.11	94.2
6	5.2	4.9-5.5	1.82 1.41	1.78 1.58	1.62	.21	87.3	1.68	.10	94.1
7	6.0	5.5-6.1	1.41 1.20	1.58 1.25	1.31	.11	92.0	1.42	.17	88.3
8	6.9	6.7-7.3	0.90 0.66	0.86 0.55	0.78	.12	84.3	0.71	.16	77.2
9	7.8	7.9-8.5	0.43 0.22	0.40 0.24	0.32	.10	68.2	0.32	.08	75.0
10	8.6	8.5-9.1	0.22 0.13	0.24 0.06	0.17	.05	72.5	0.15	.09	41.3

* $Uc\% = 100(1 - \frac{\Delta\bar{y}}{\bar{y}})$

Table 4a. Uniformity of application moving down each line parallel to the line source.

Row	Average depth* of water at A and B	y	$\lvert\Delta\bar{y}\rvert$	Uc%	% of row 1
1	2.87 2.95	2.91	.04	98.6	100.0
2	2.79 2.78	2.79	.005	99.8	95.9
3	2.52 2.65	2.59	.065	97.5	89.0
4	2.39 2.30	2.35	.045	98.1	80.8
5	1.96 1.89	1.93	.035	98.2	66.3
6	1.62 1.68	1.65	.03	98.2	56.7
7	1.31 1.42	1.37	.055	96.0	47.1
8	0.78 0.71	0.75	.033	95.6	25.6
9	0.32 0.32	0.32	.002	99.5	11.1
10	0.17 0.15	0.16	.012	92.9	5.6

* Depth of water is in arbitrary units.

APPENDIX B

SOIL MOISTURE RELEASE CURVES

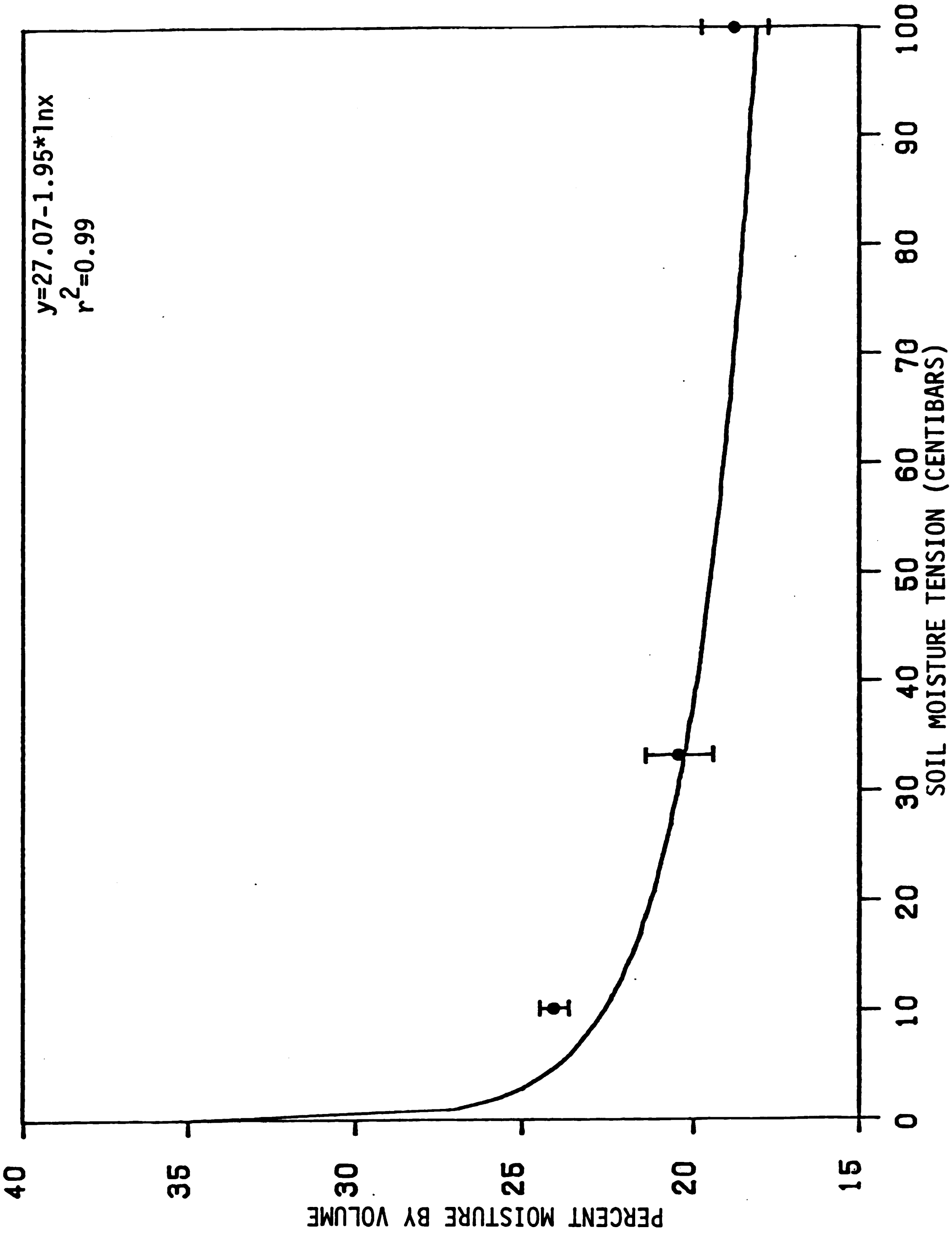

Fig. 1b. Range 1; Metea loamy sand; 0-10 cm.

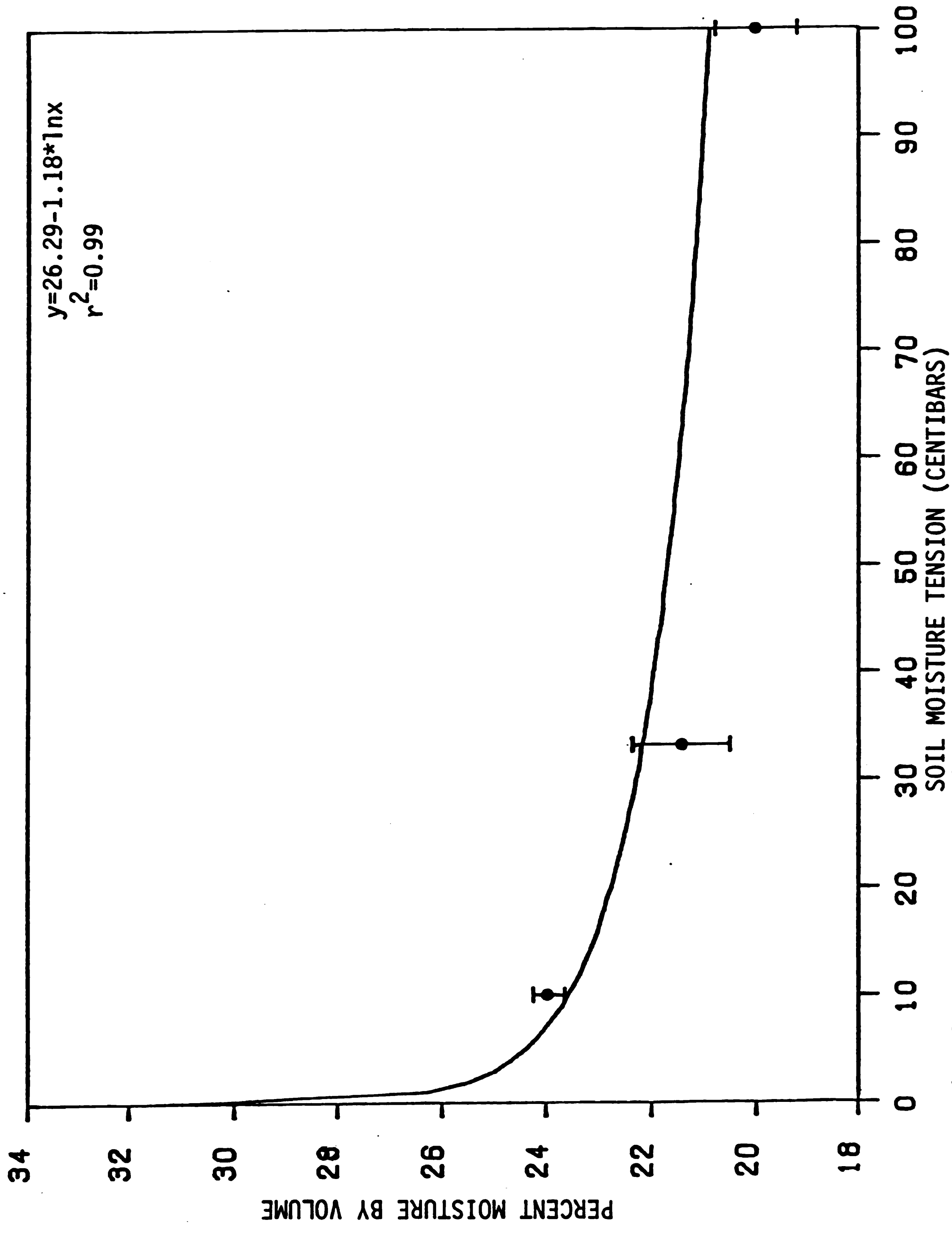

Fig. 2b. Range 1; Metea loamy sand; 46-56 cm.

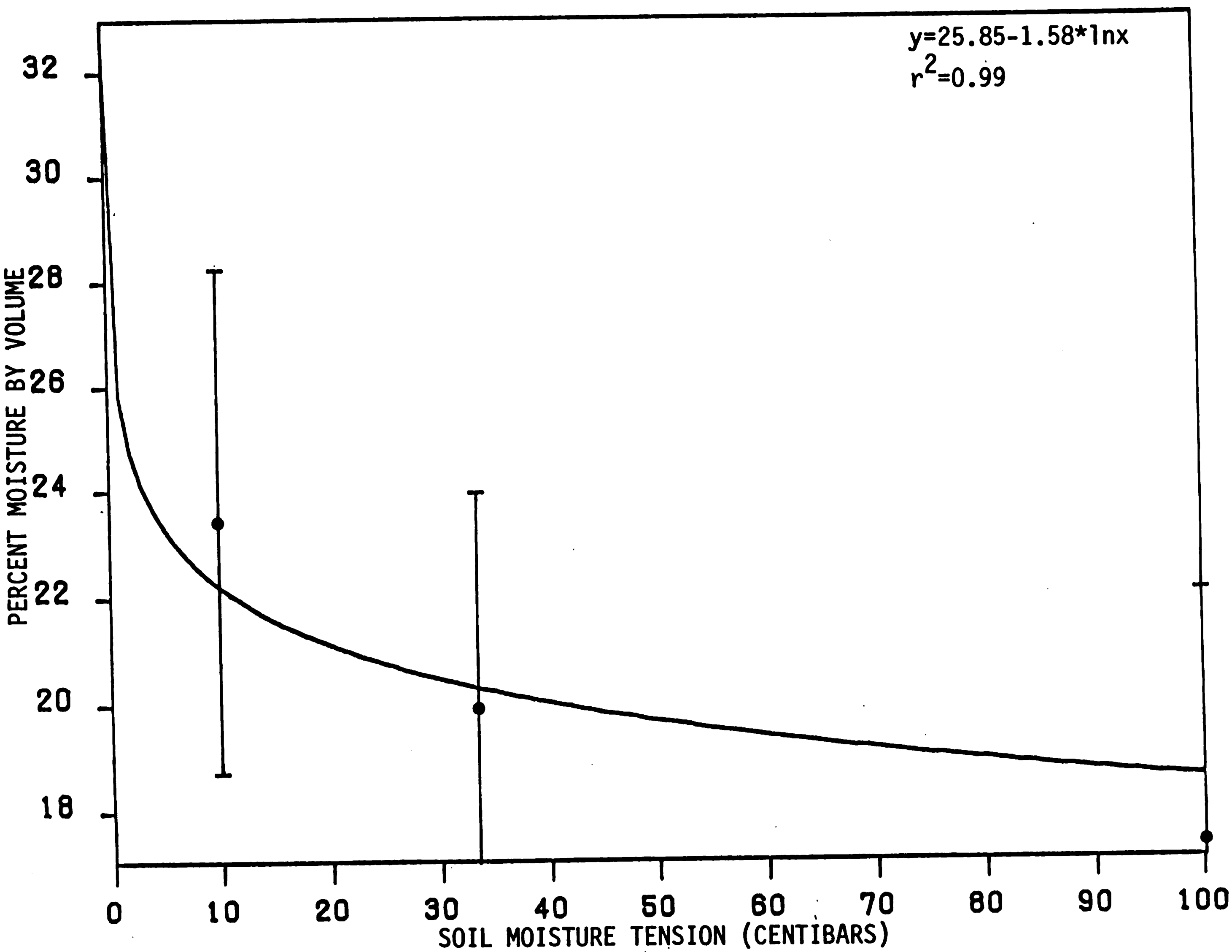

Fig. 3b. Range 1; Metea loamy sand; 76-86 cm.

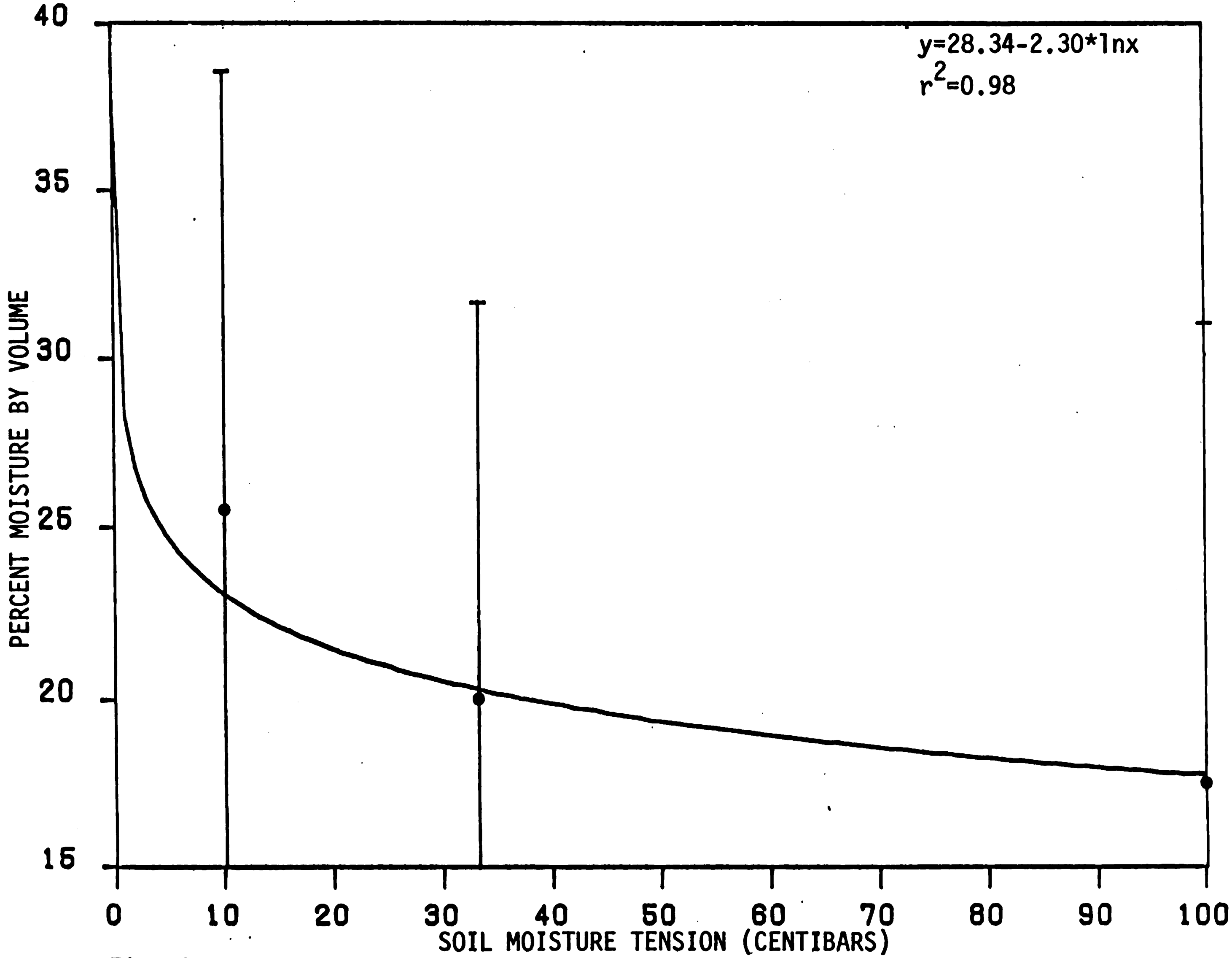

Fig. 4b. Range 2; Metea loamy sand; 0-10 cm.

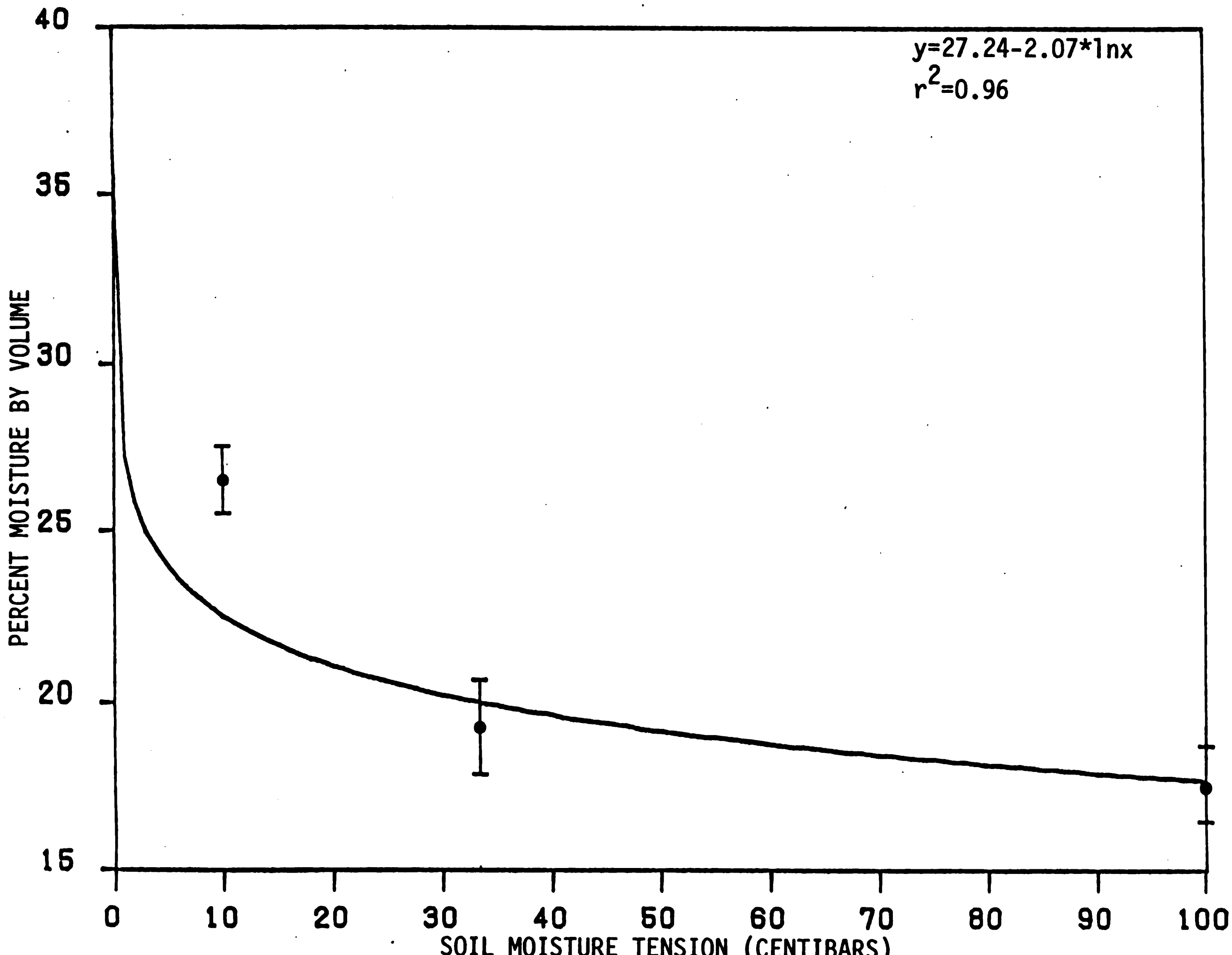

Fig. 5b. Range 2; Metea loamy sand; 31-41 cm.

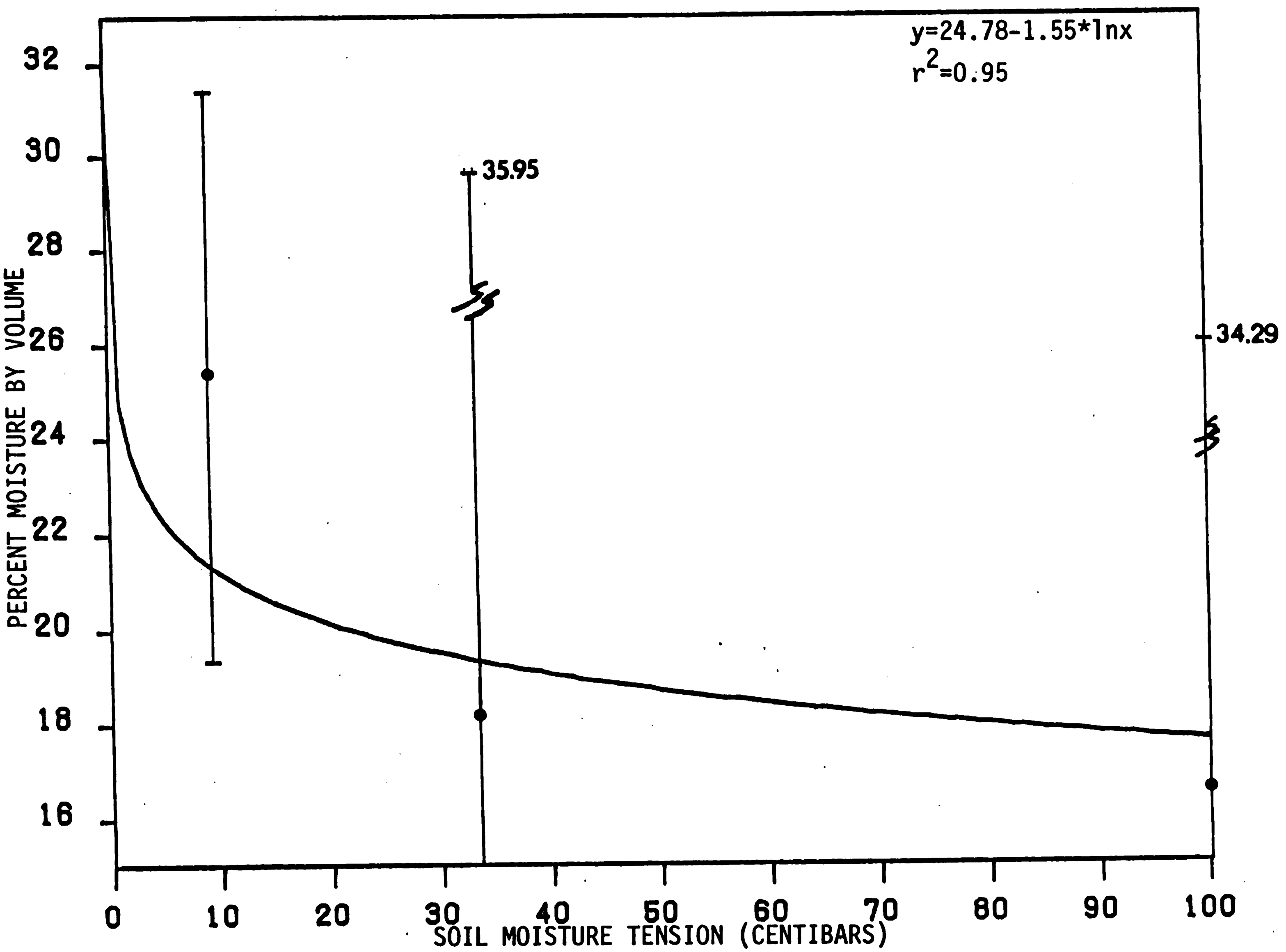

Fig. 6b. Range 2; Metea loamy sand; 76-86 cm.

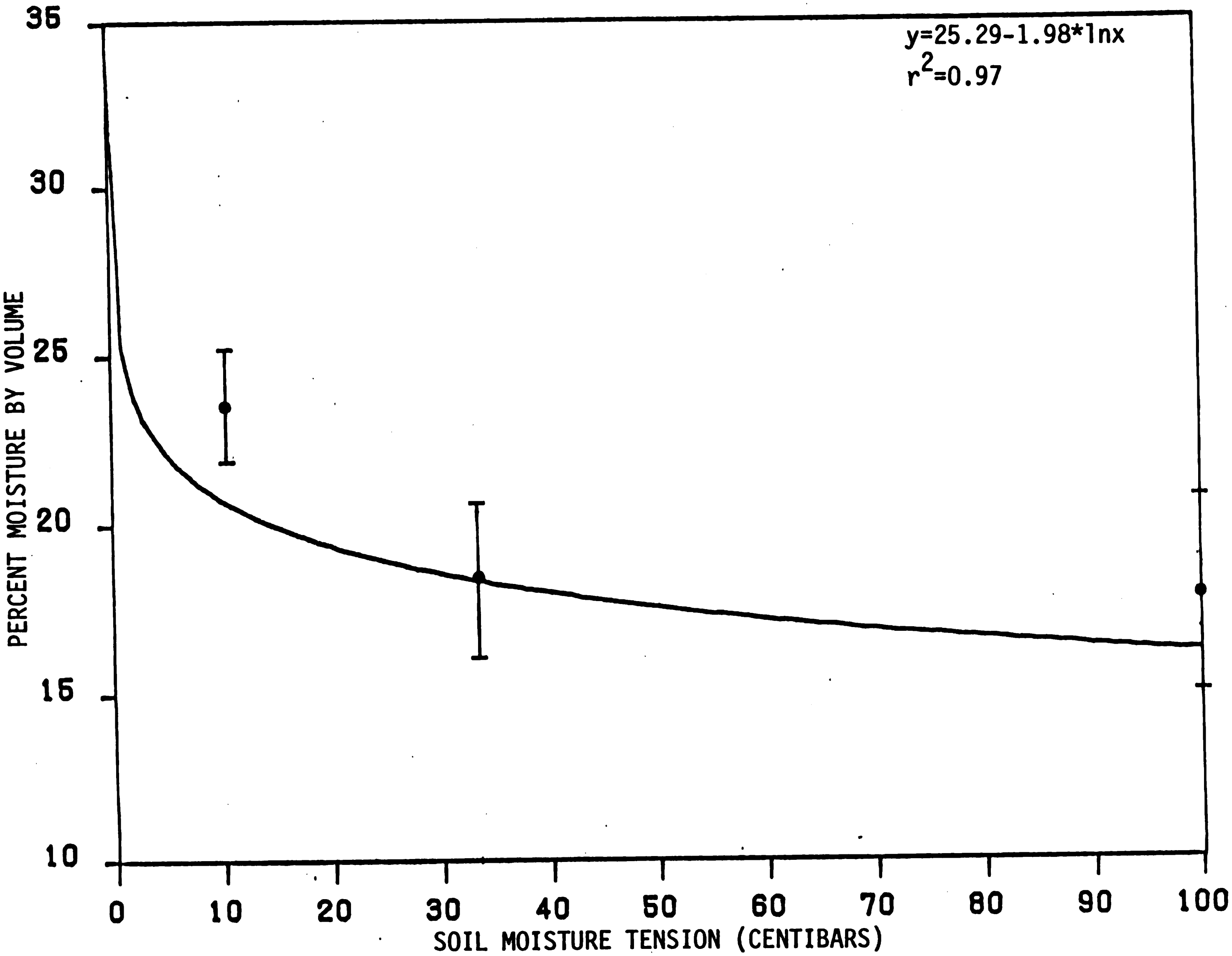

Fig. 7b. Range 3; Metea loamy sand; 0-10 cm.

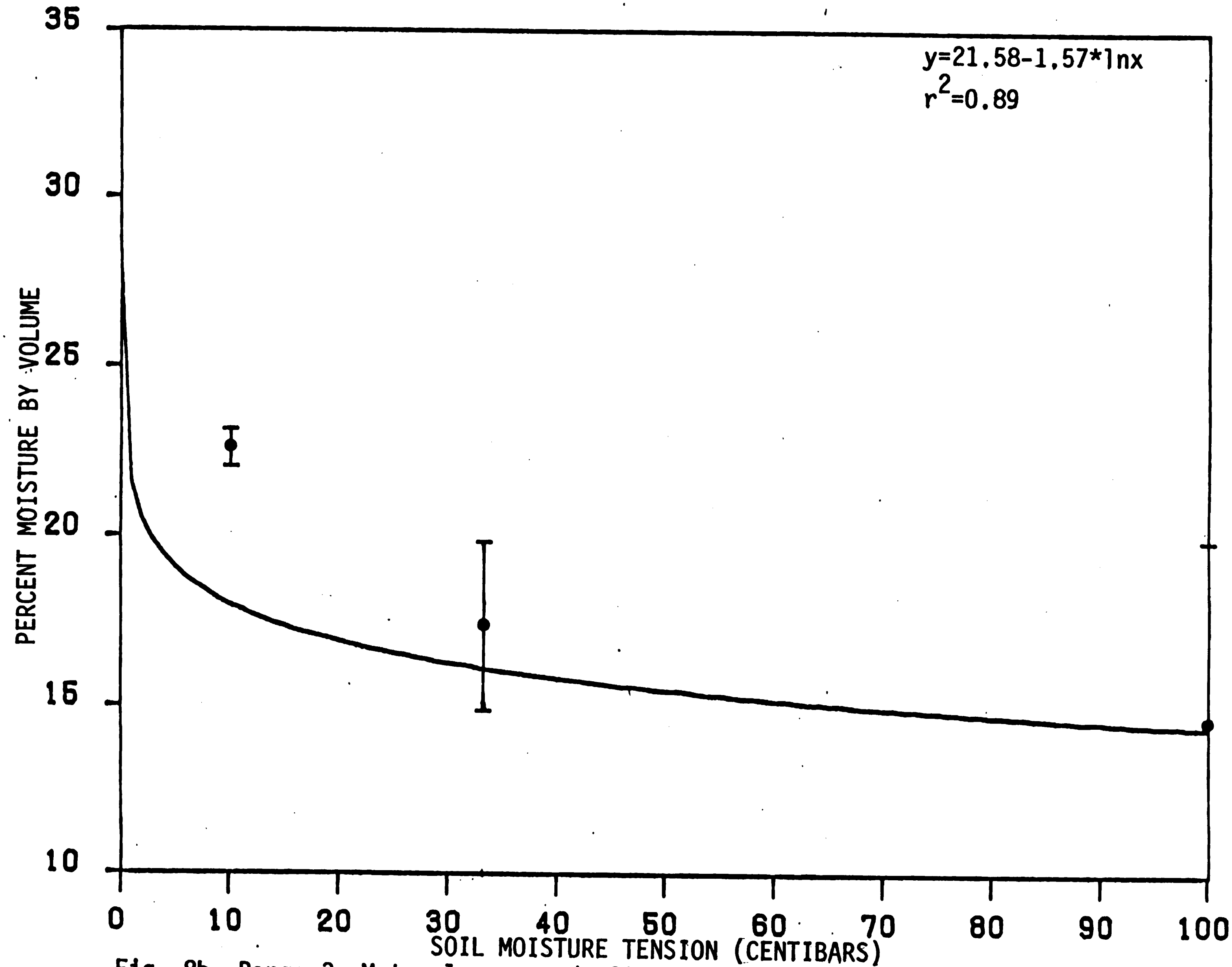

Fig. 8b. Range 3; Metea loamy sand; 38-48 cm.

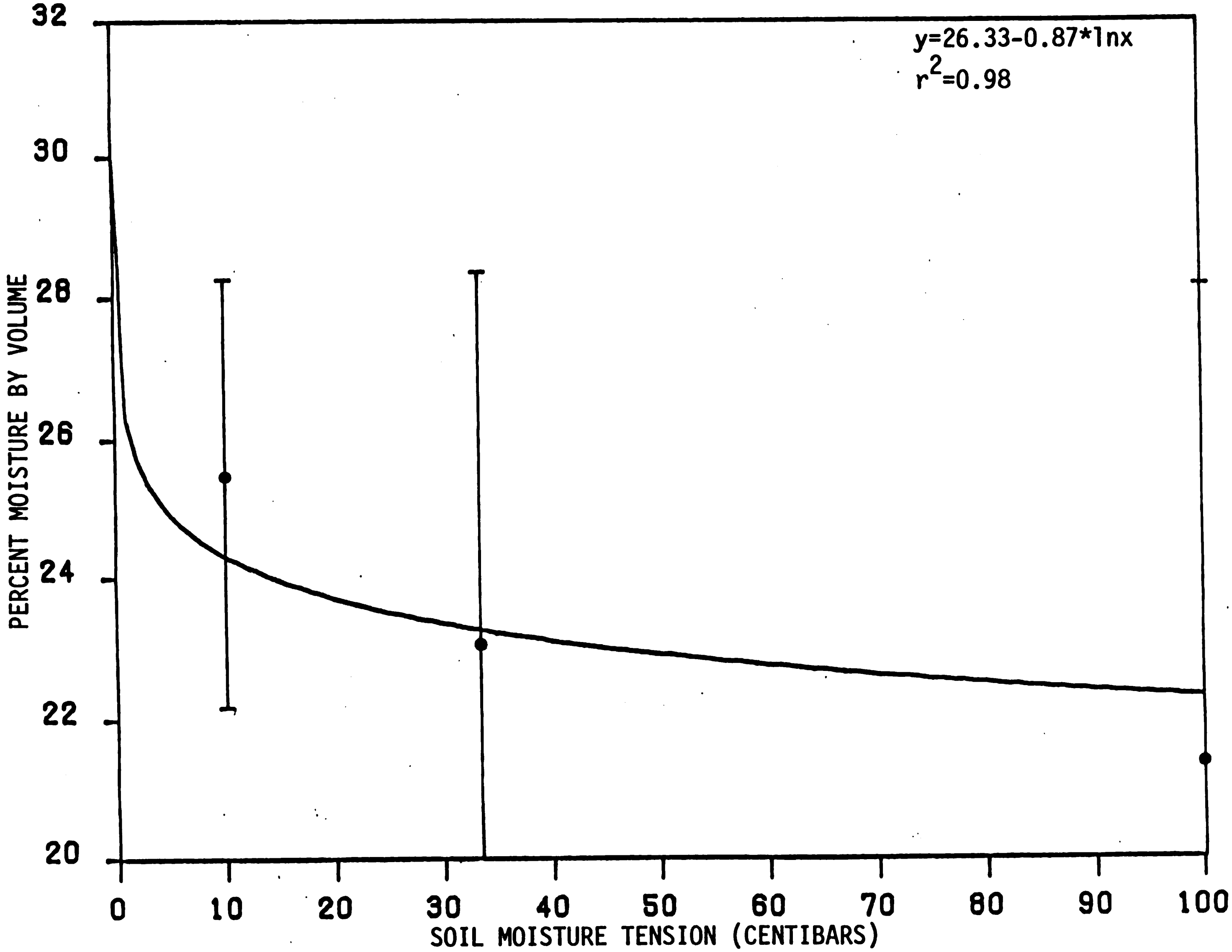

Fig. 9b. Range 3; Metea loamy sand; 69-79 cm.

APPENDIX C

WATER INPUTS TO THE PLOT
RAINFALL PLUS IRRIGATION

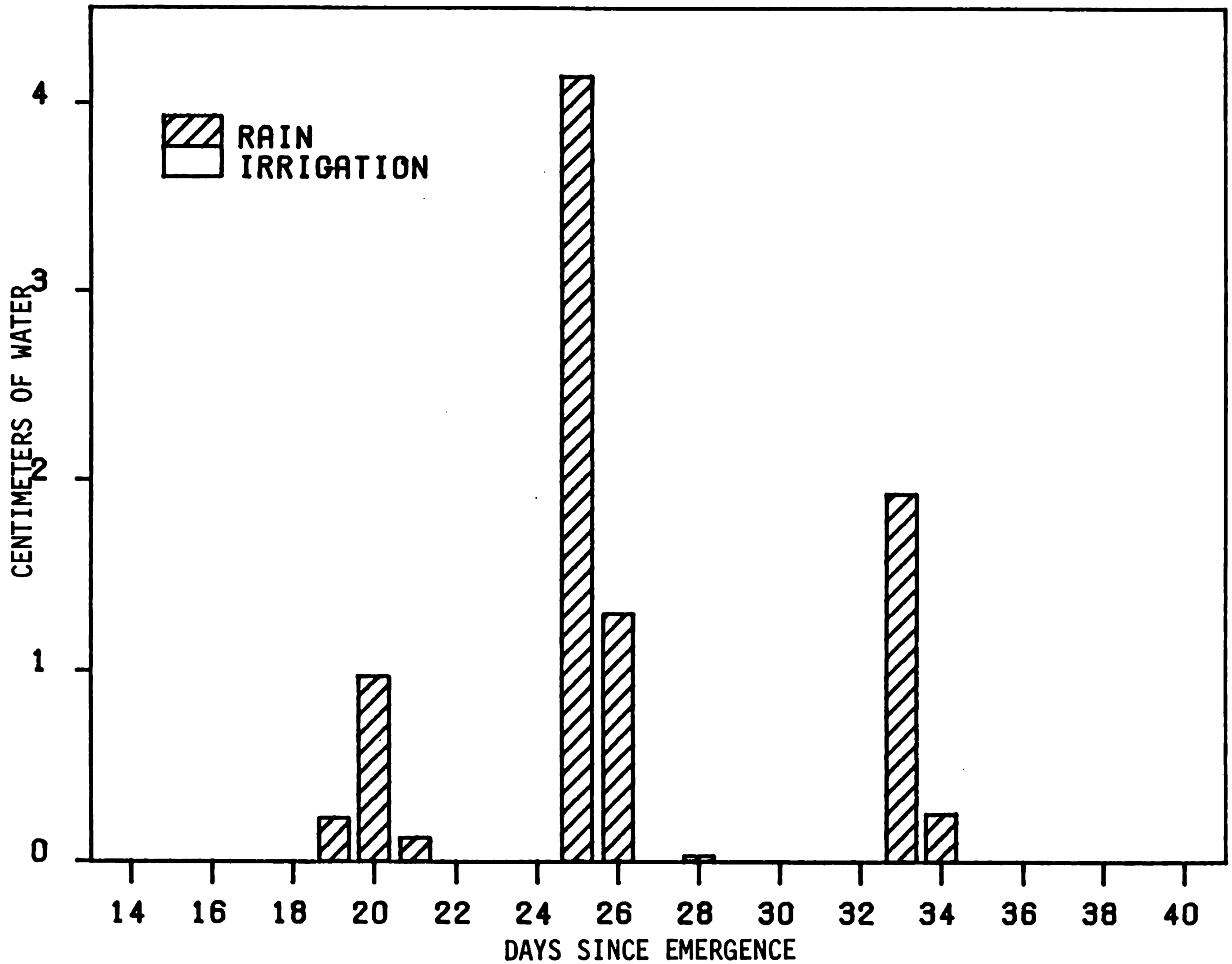

Fig. 1c. Water inputs to the plot; rain plus irrigation.

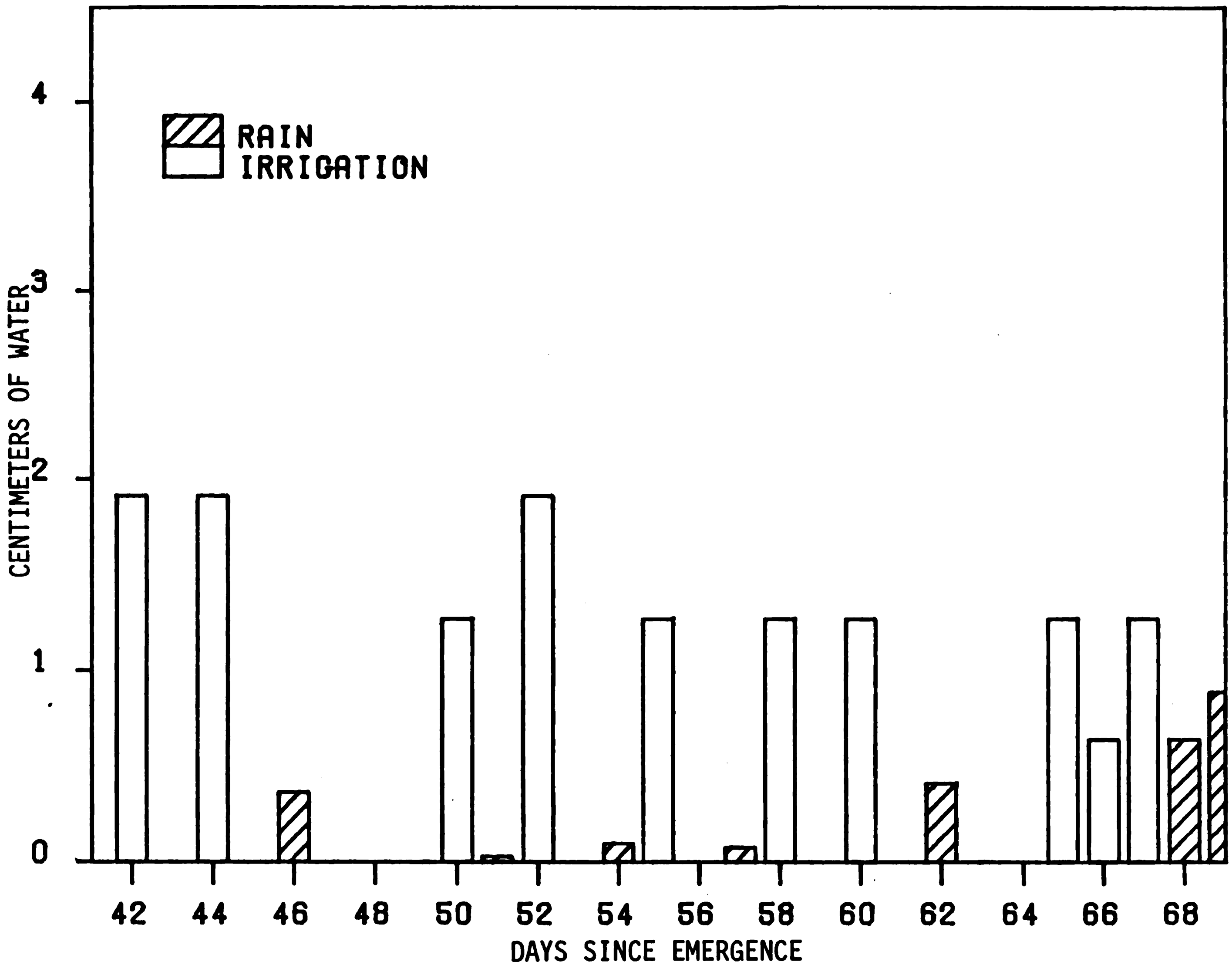

Fig. 2c. Water inputs to the plot; rain plus irrigation.

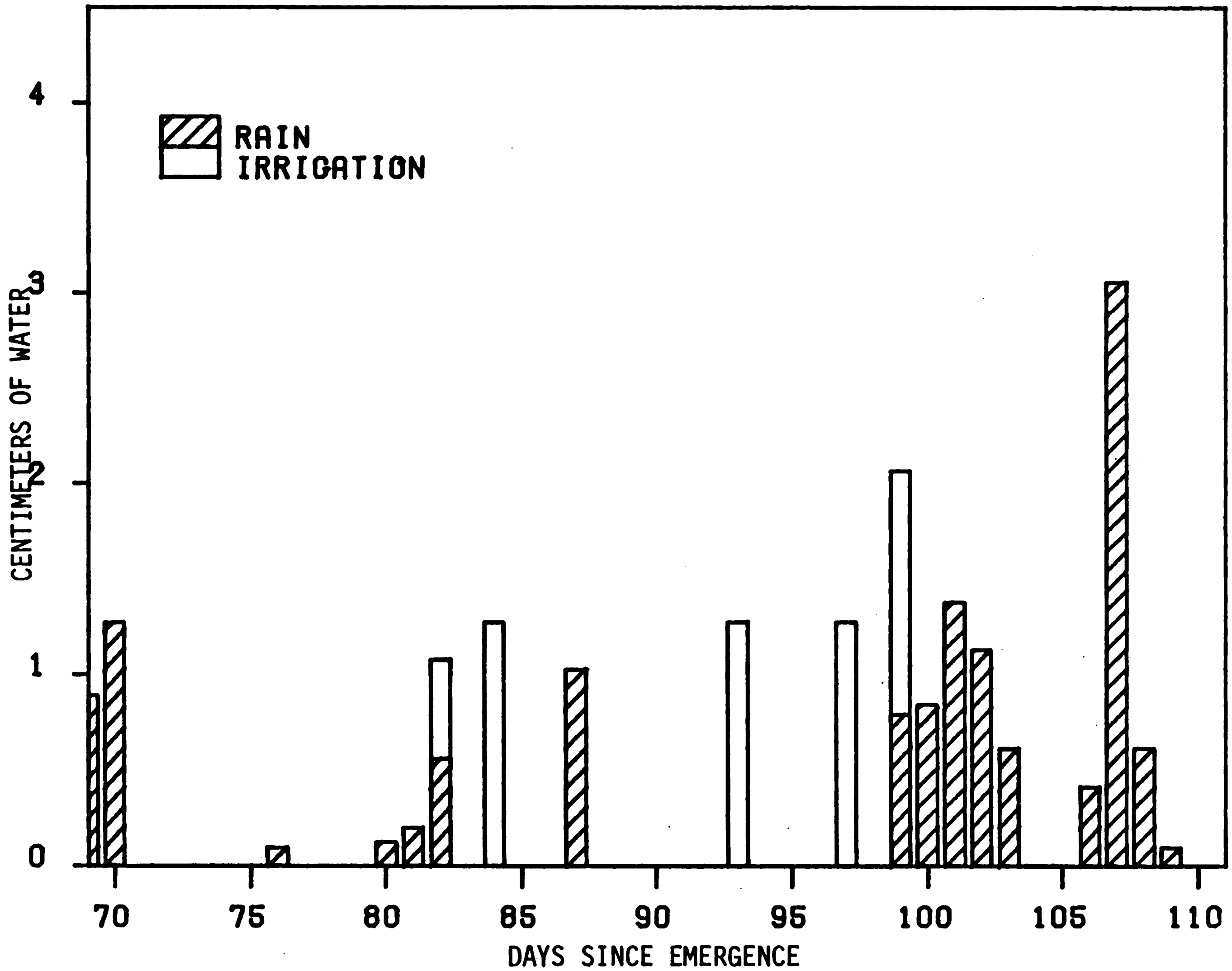

Fig. 3c. Water inputs to the plot; rain plus irrigation.

APPENDIX D

TENSIOMETER READINGS DURING SEASON
CENTIBARS AND PERCENT MOISTURE BY VOLUME

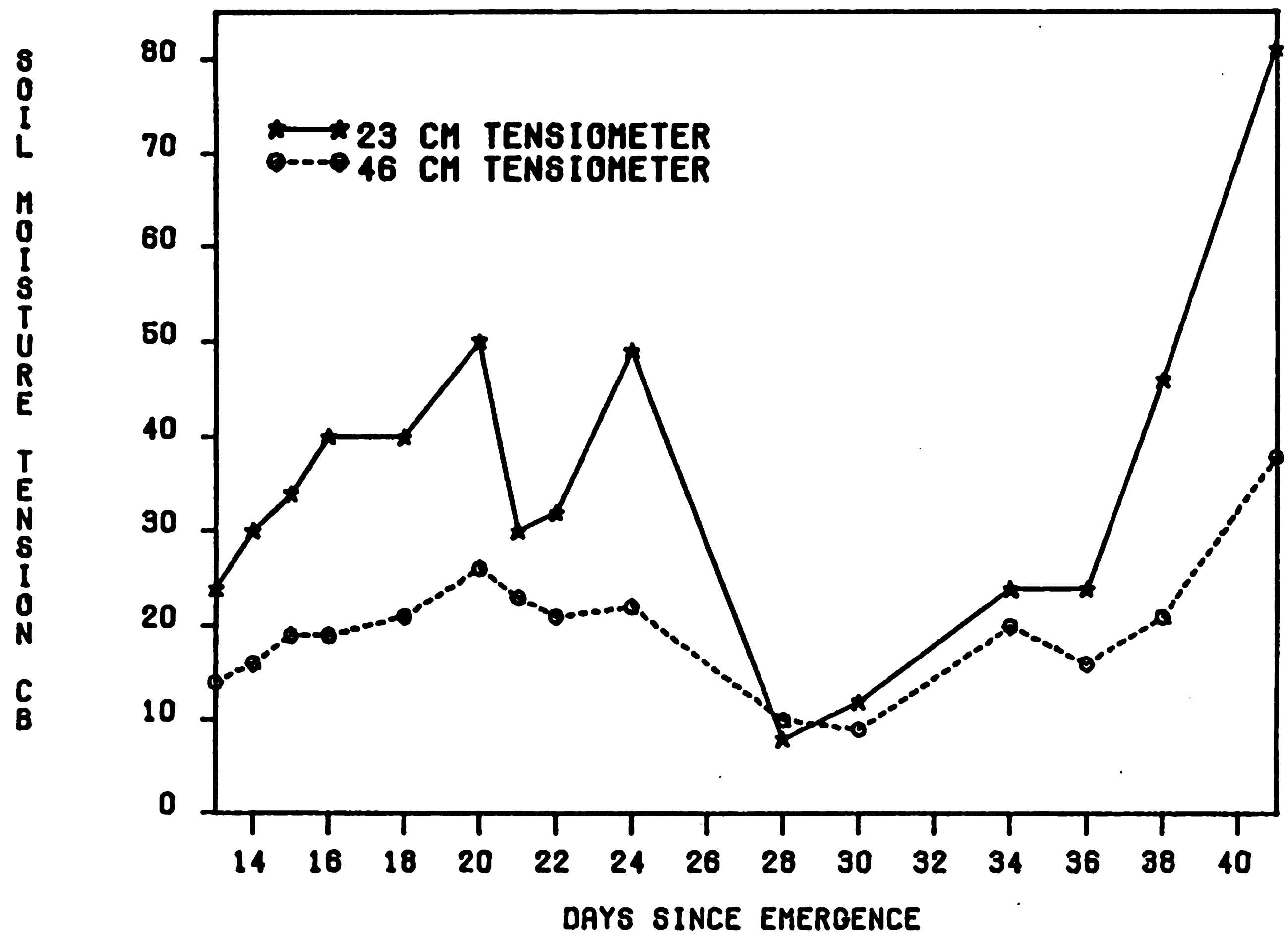

Fig. 1d. Range 1 tensiometer readings.

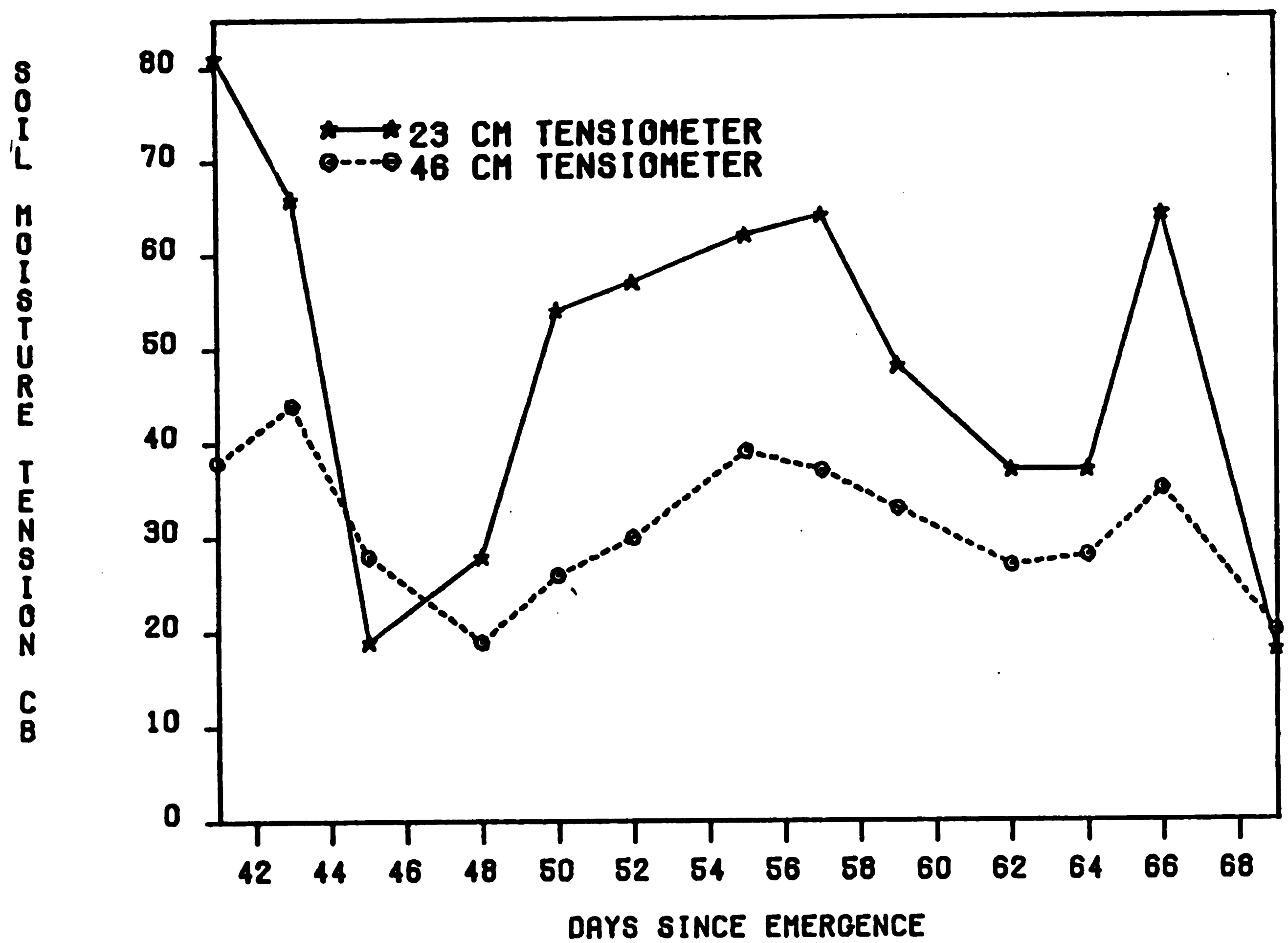

Fig. 2d. Range 1 tensiometer readings.

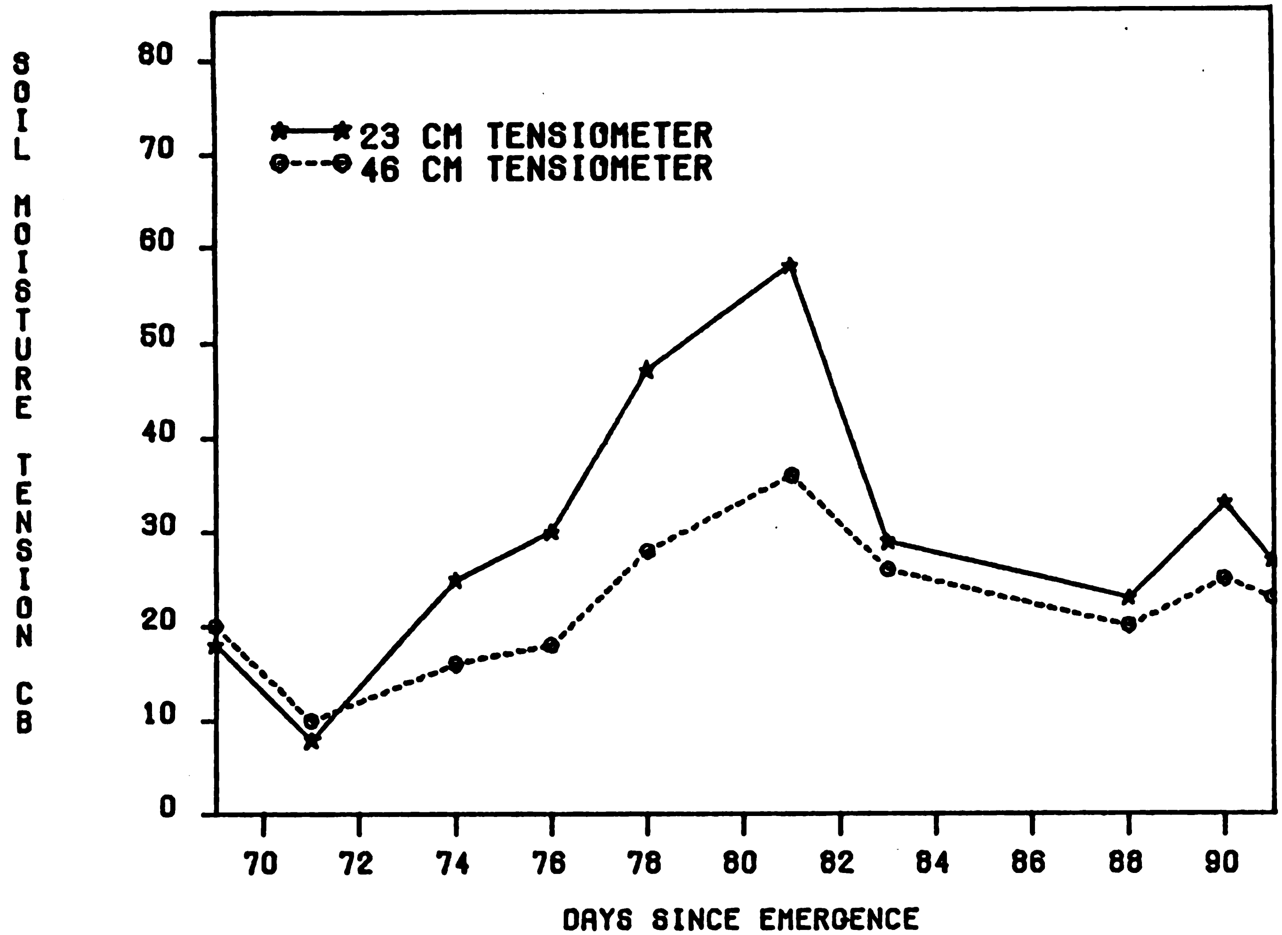

Fig. 3d. Range 1 tensiometer readings.

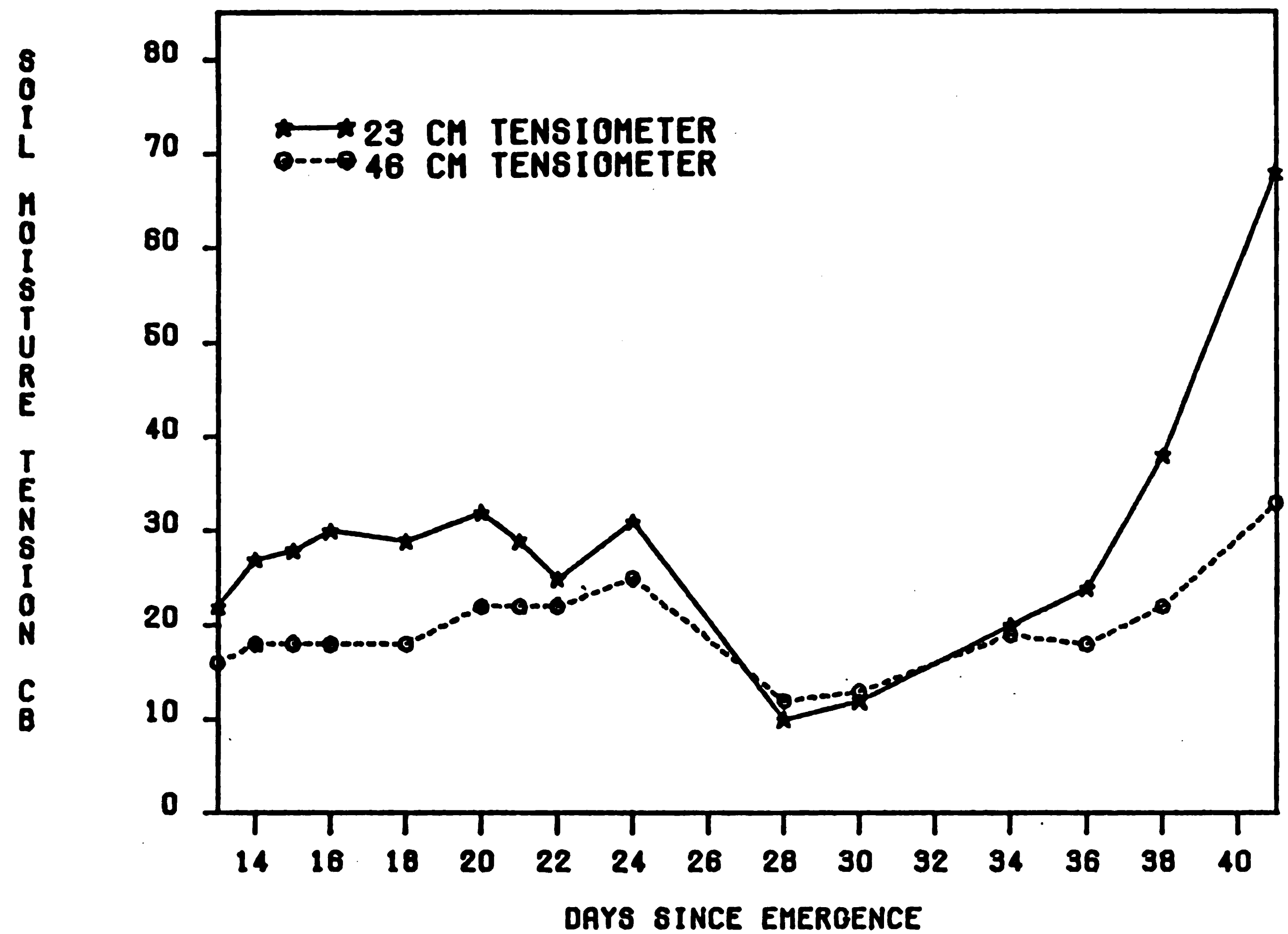

Fig. 4d. Range 2 tensiometer readings.

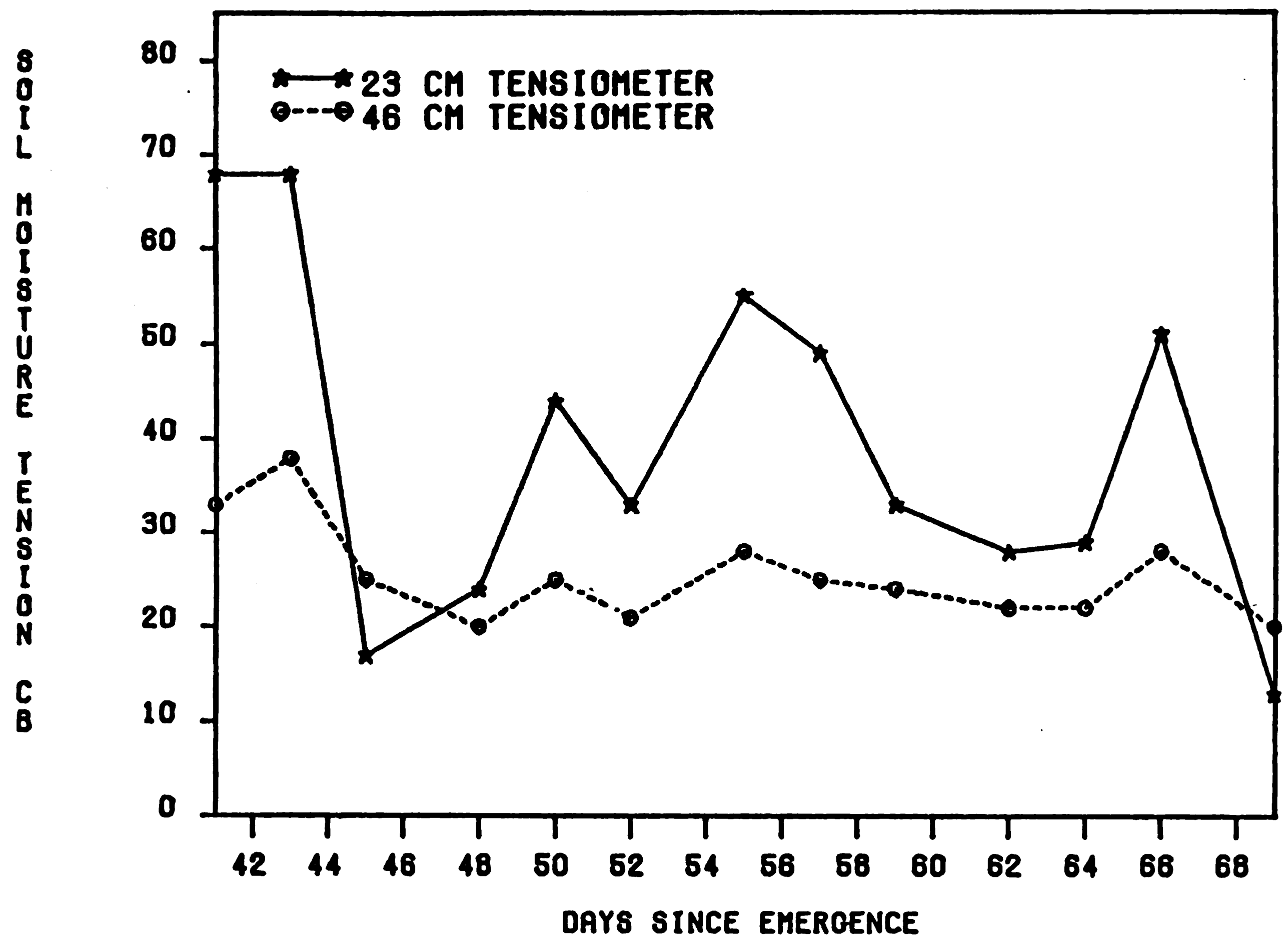

Fig. 5d. Range 2 tensiometer readings.

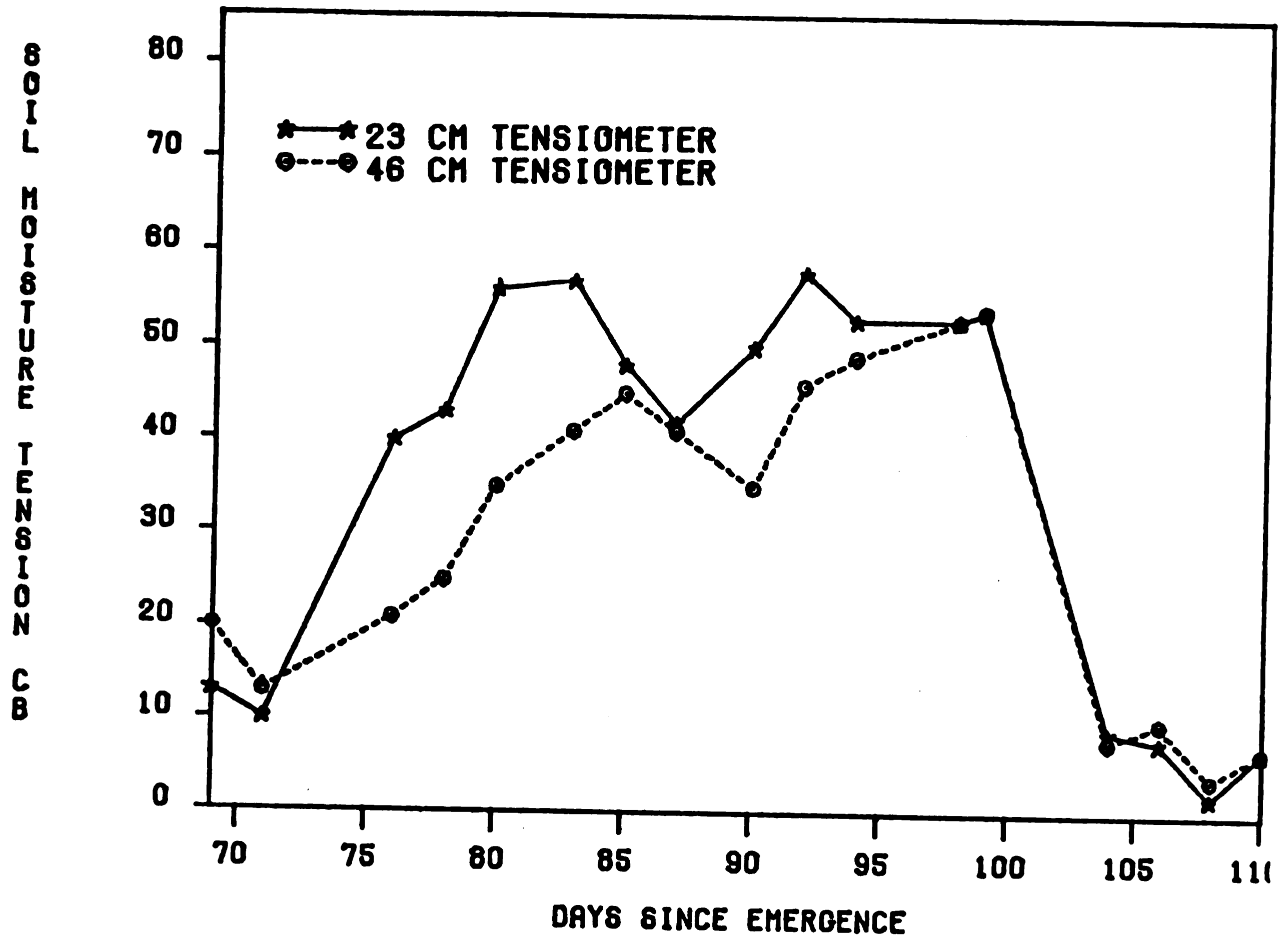

Fig. 6d. Range 2 tensiometer readings.

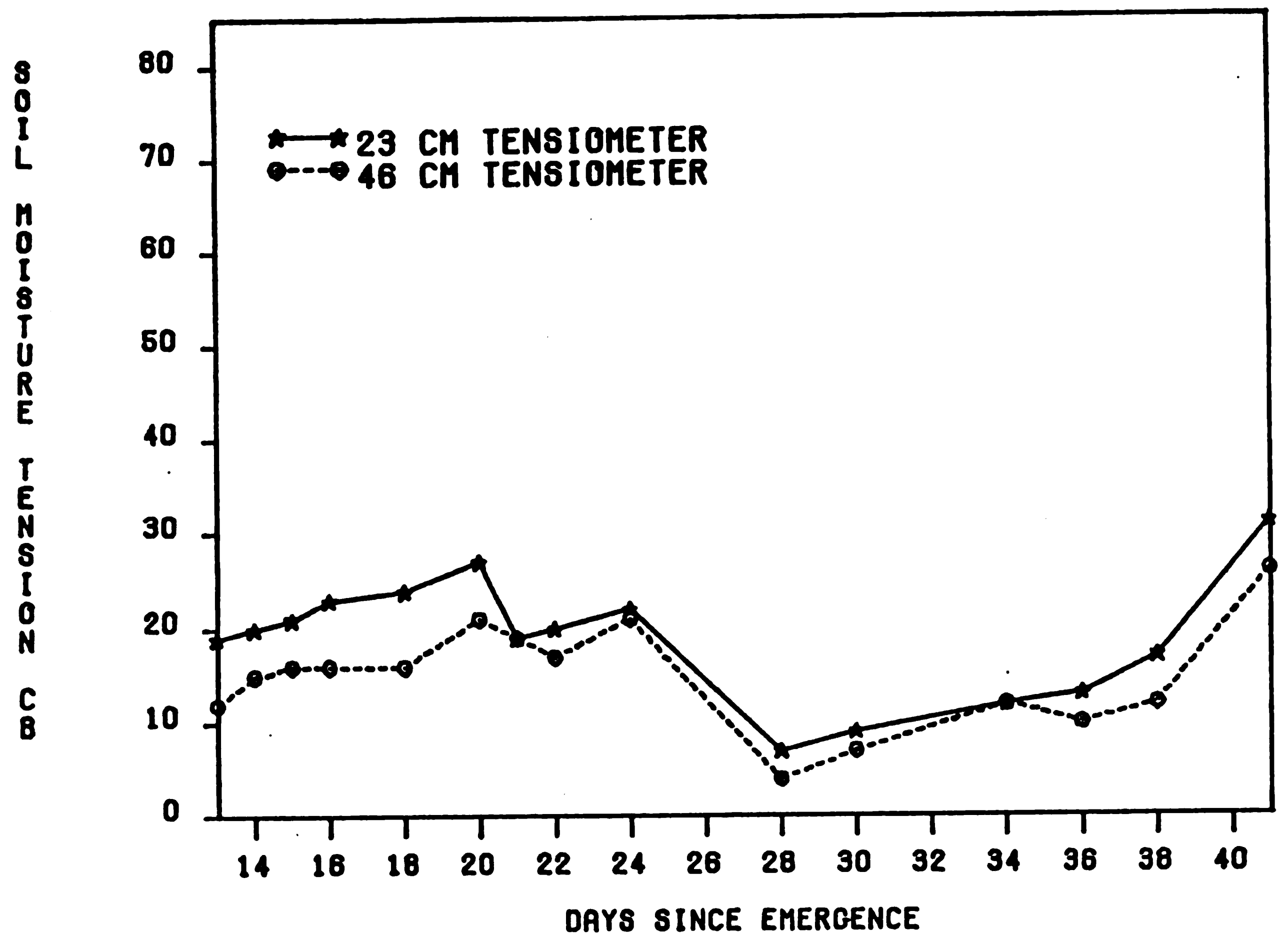

Fig. 7d. Range 3 tensiometer readings.

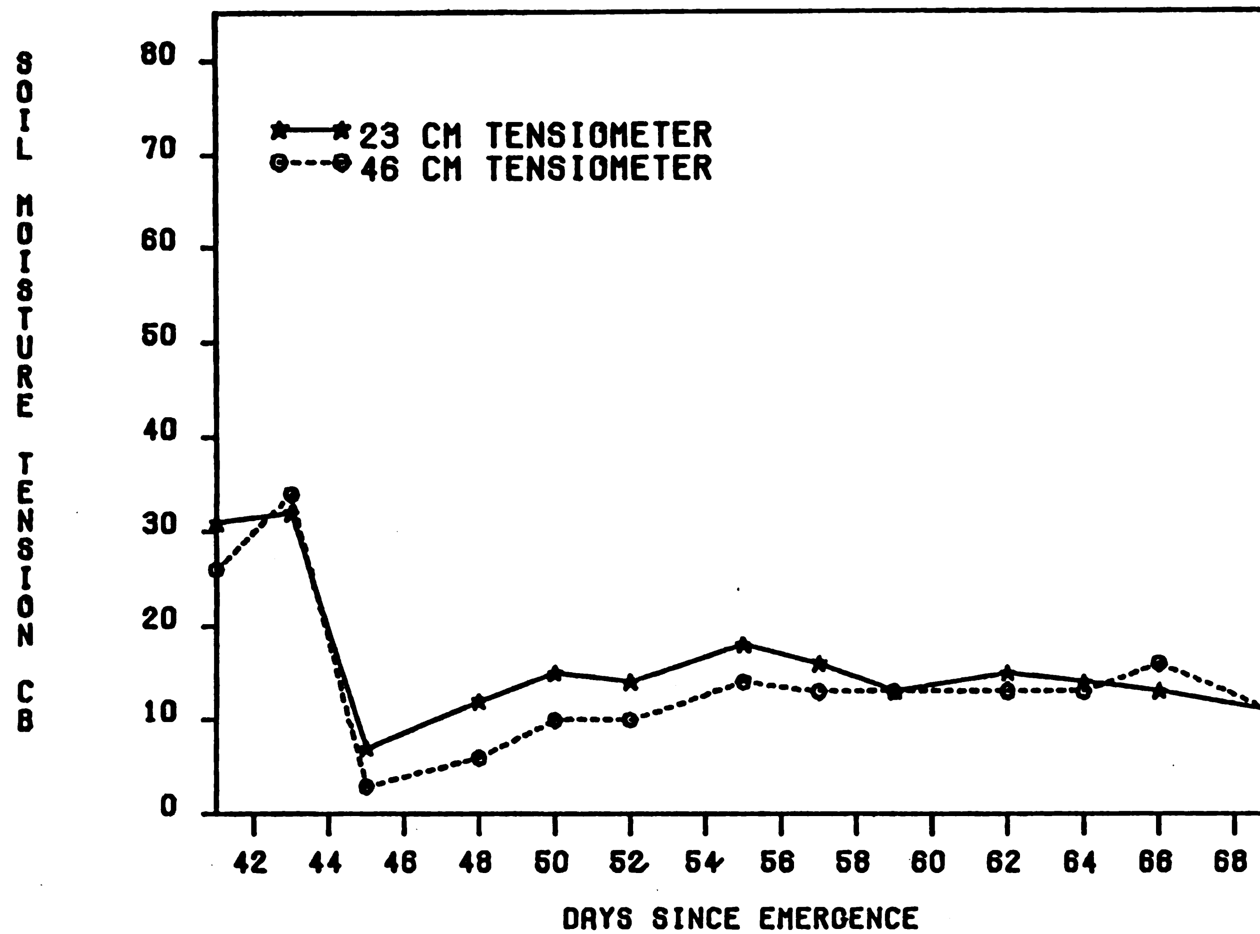

Fig. 8d. Range 3 tensiometer readings.

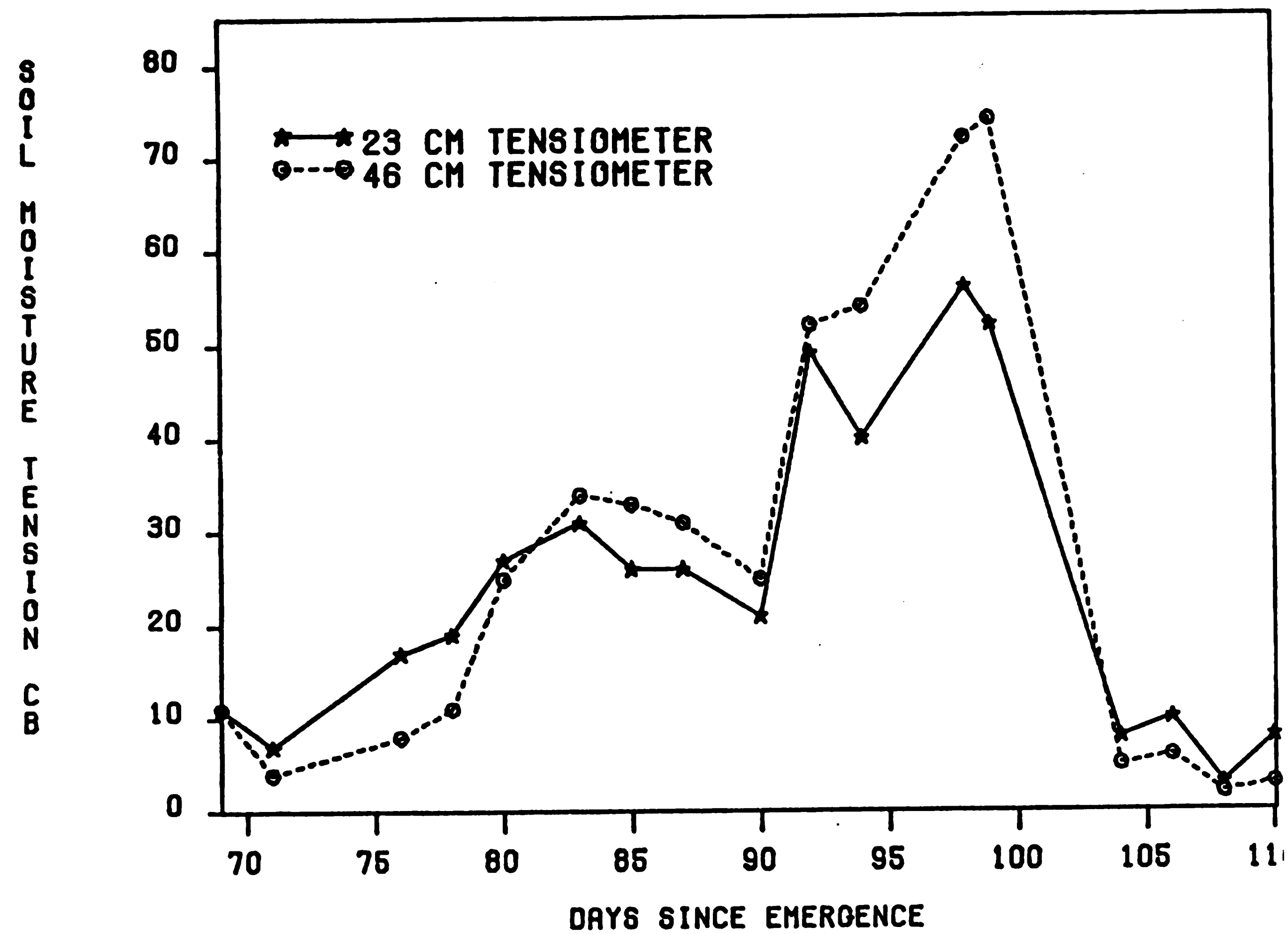

Fig. 9d. Range 3 tensiometer readings.

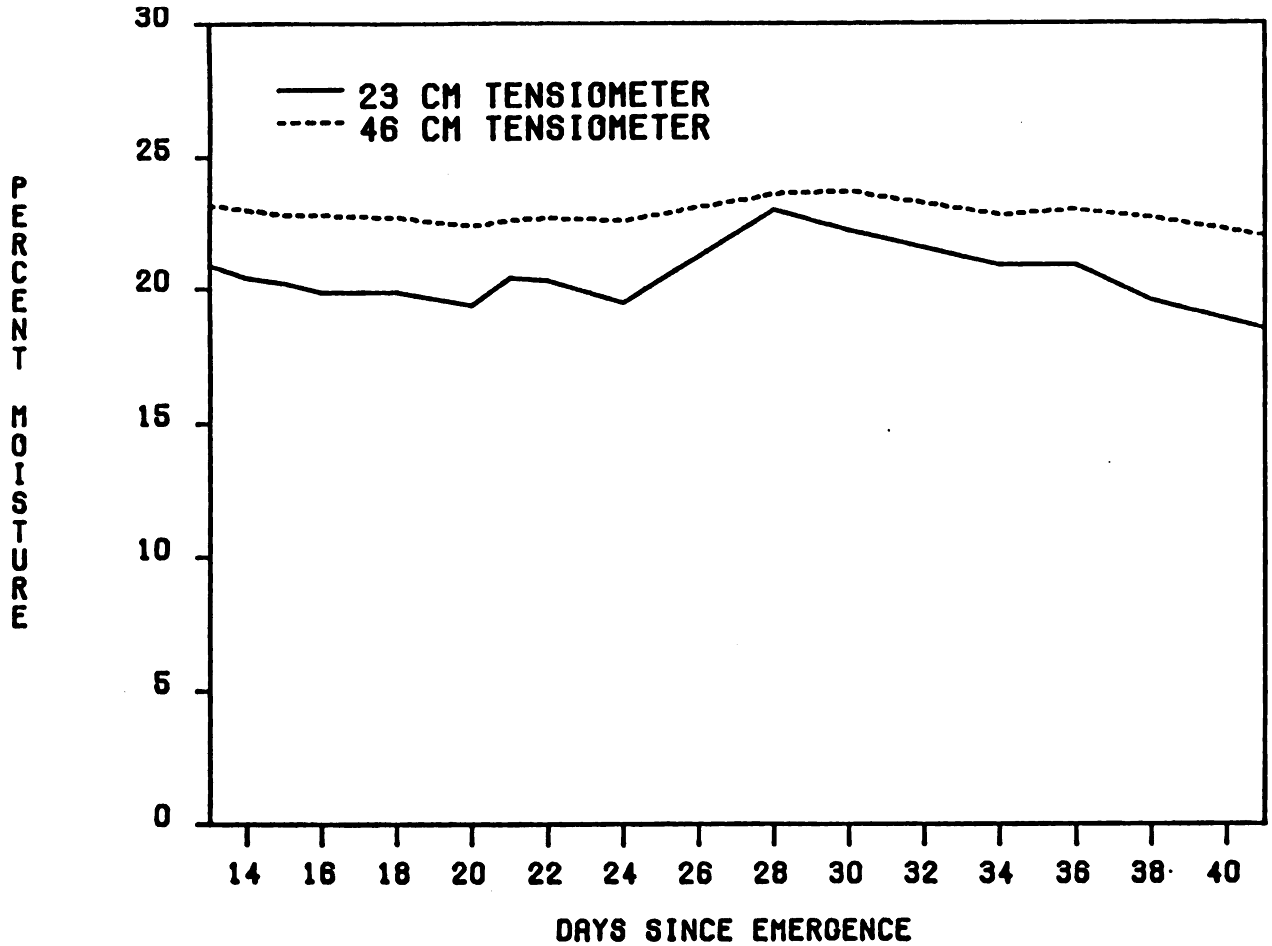

Fig. 10d. Range 1 tensiometer readings converted to percent volumetric moisture.

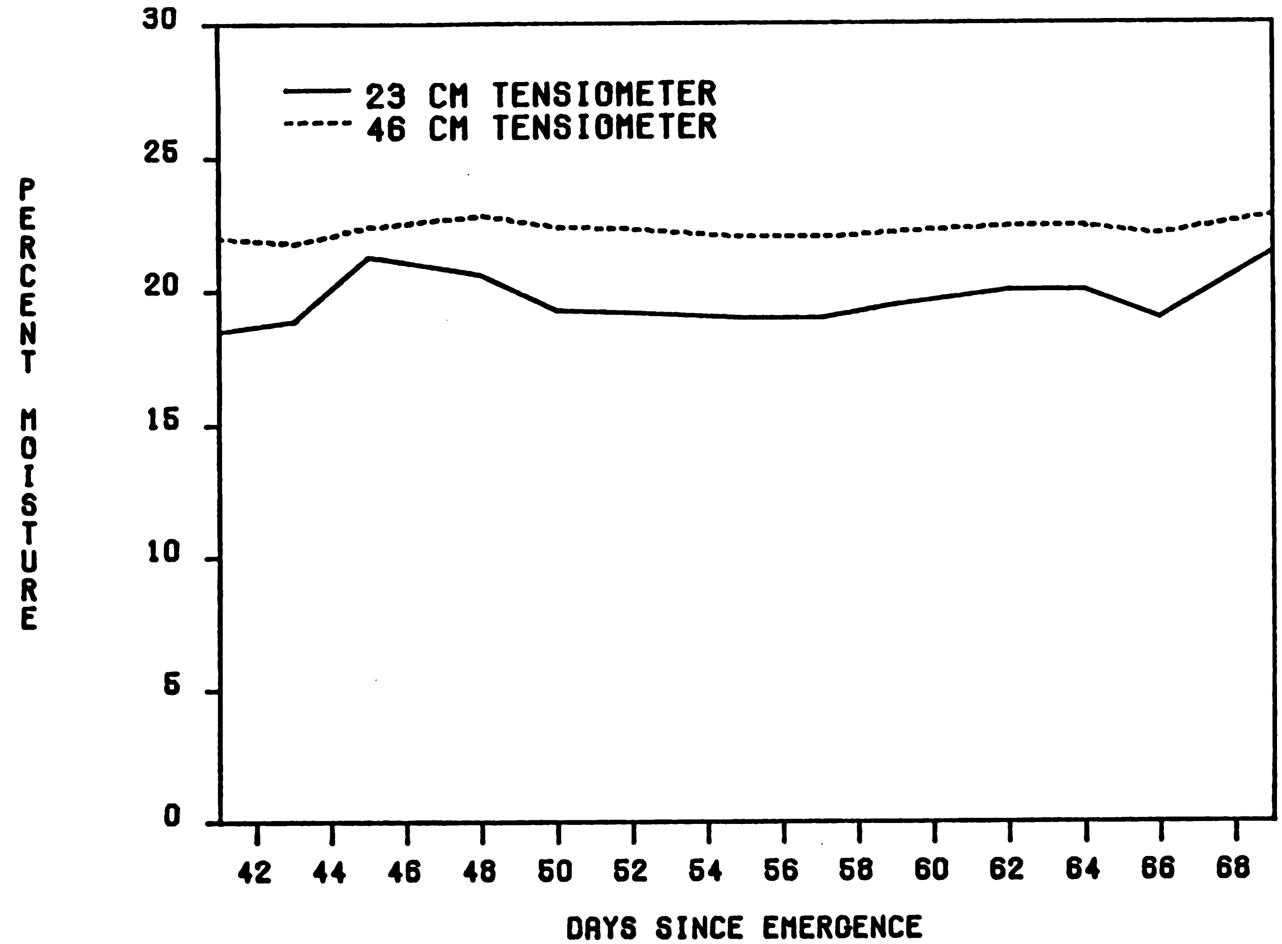

Fig. 11d. Range 1 tensiometer readings converted to volumetric percent moisture.

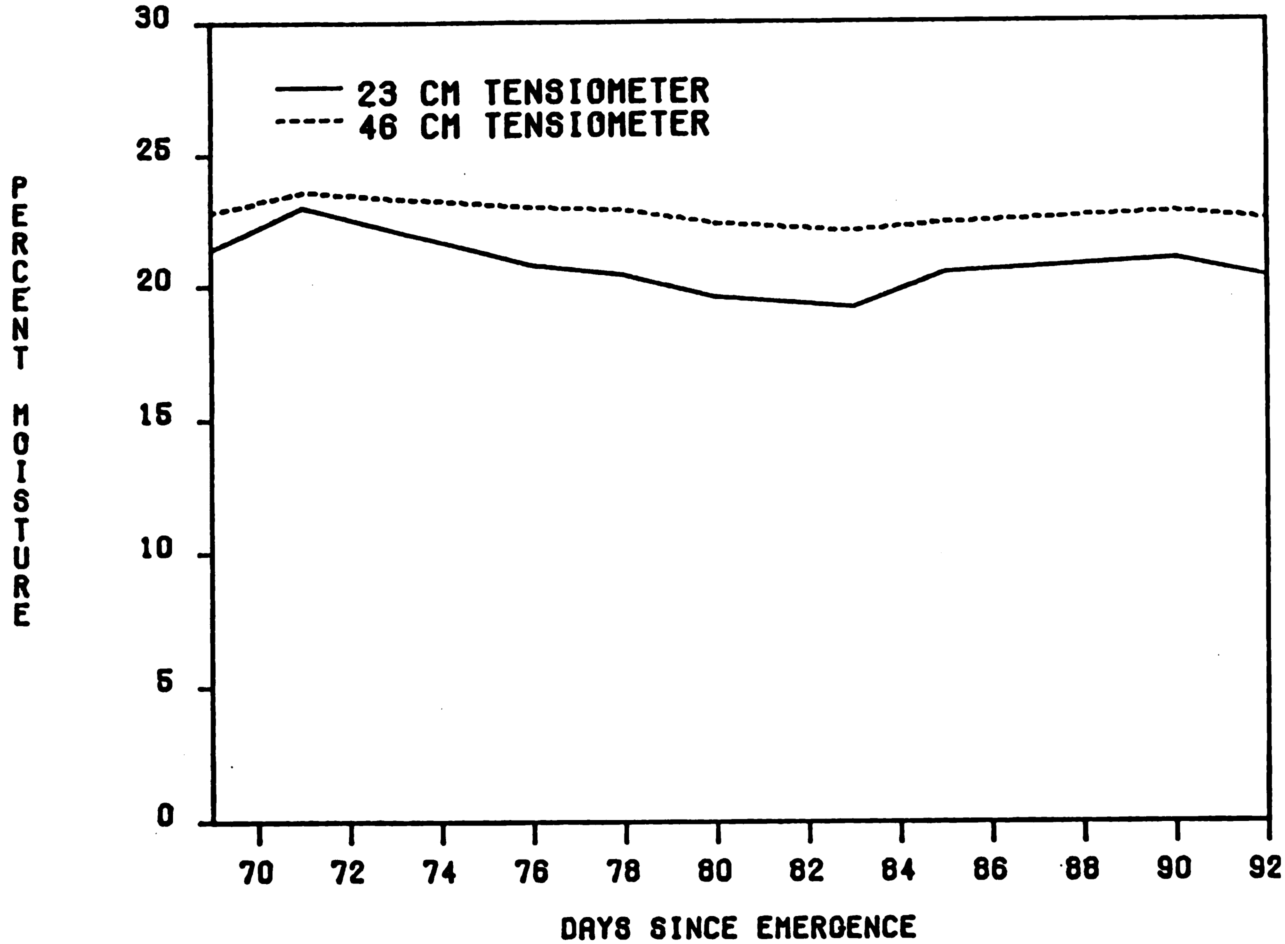

Fig. 12d. Range 1 tensiometer readings converted to volumetric percent moisture.

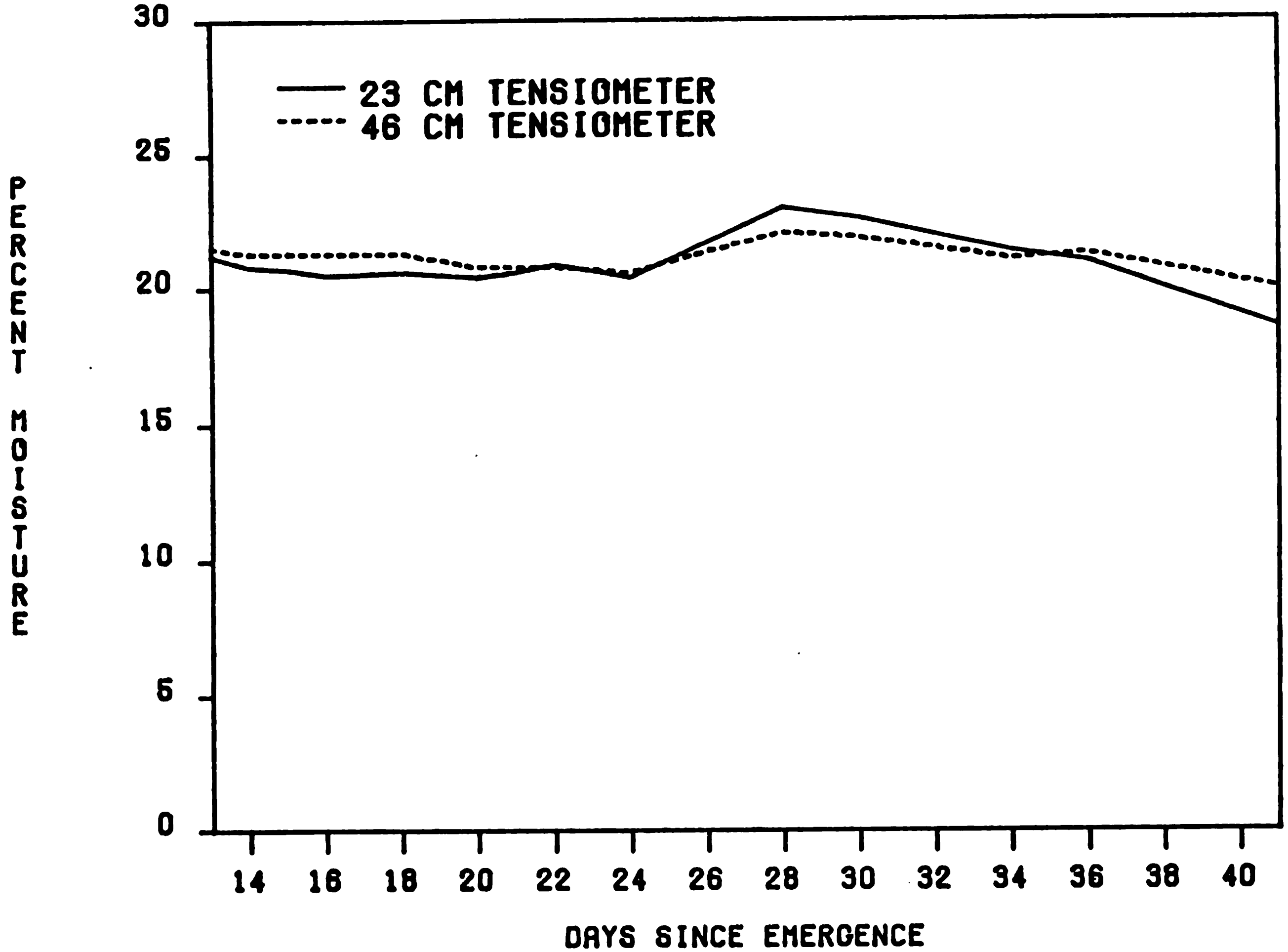

Fig. 13d. Range 2 tensiometer readings converted to volumetric percent moisture.

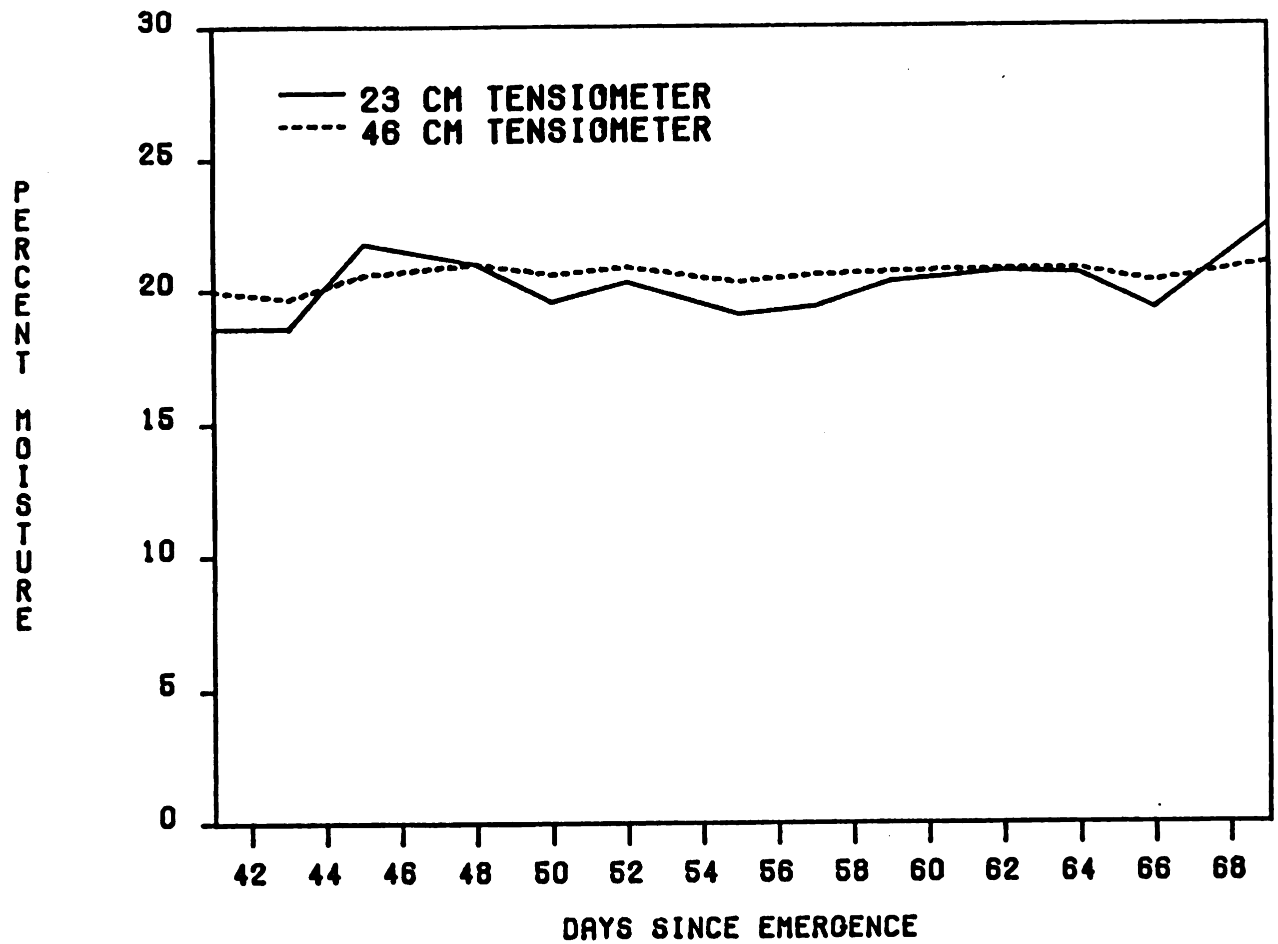

Fig. 14d. Range 2 tensiometer readings converted to volumetric percent moisture.

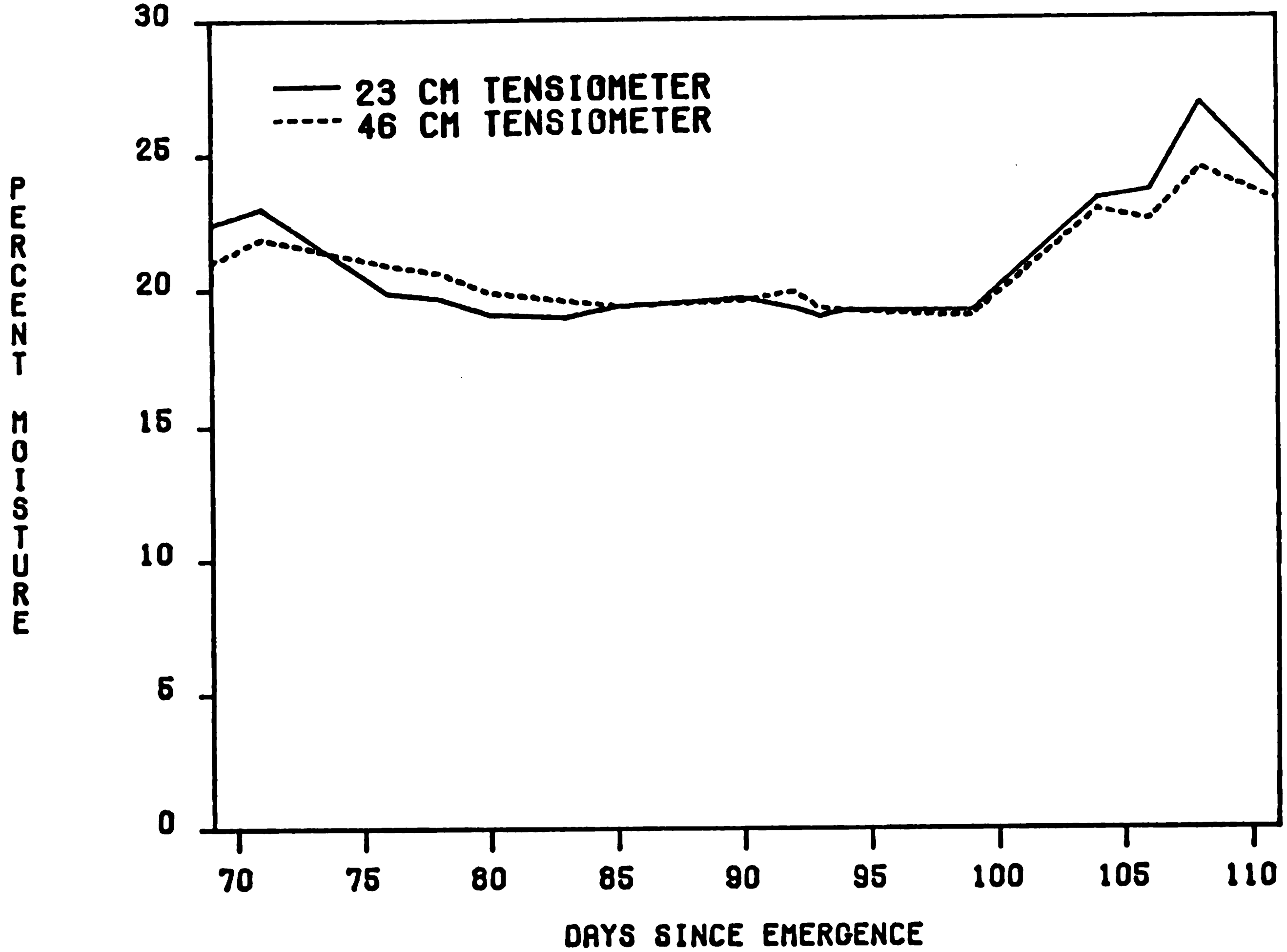

Fig. 15d. Range 2 tensiometer readings converted to volumetric percent moisture.

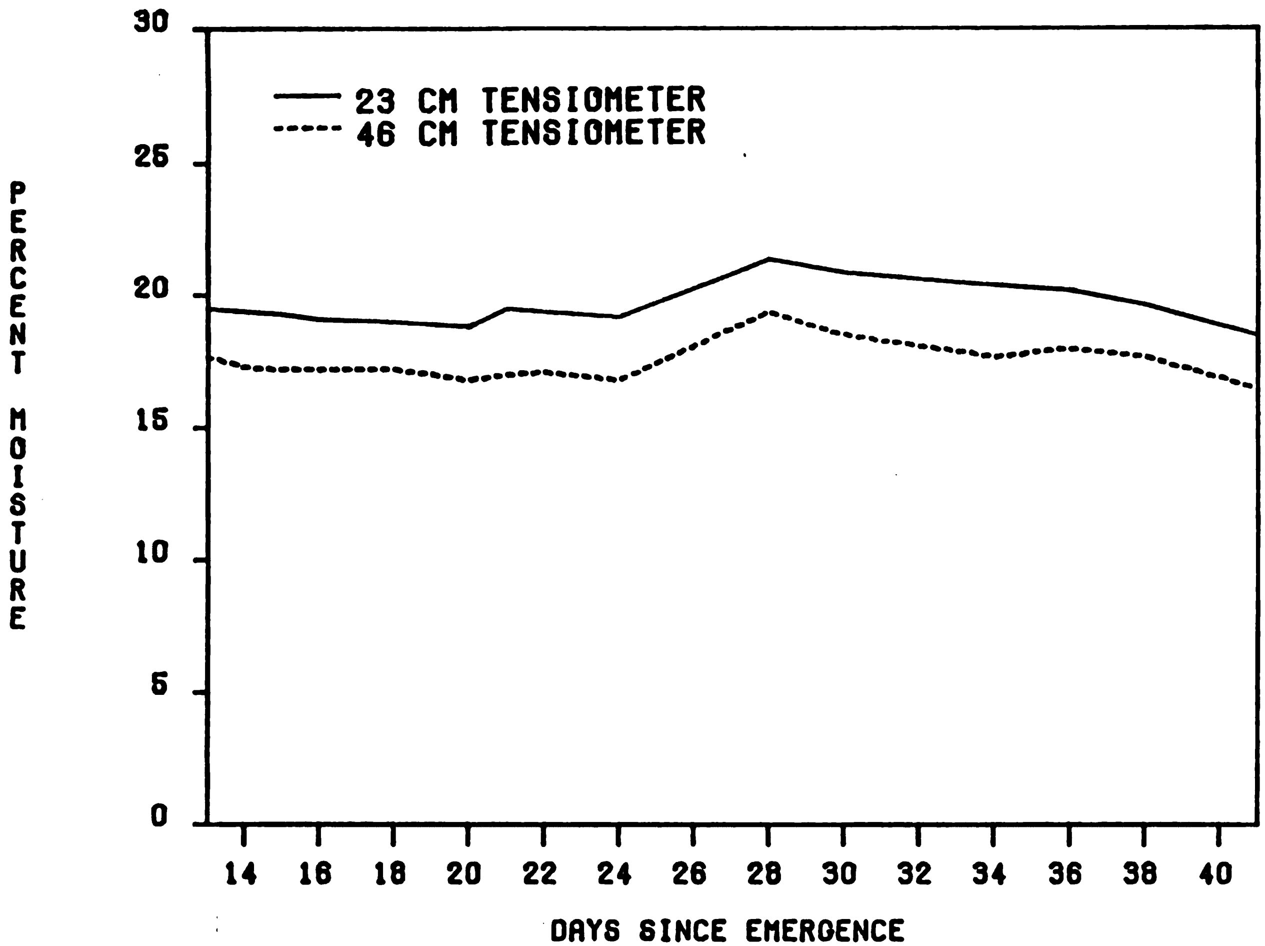

Fig. 16d. Range 3 tensiometer readings converted to volumetric percent moisture.

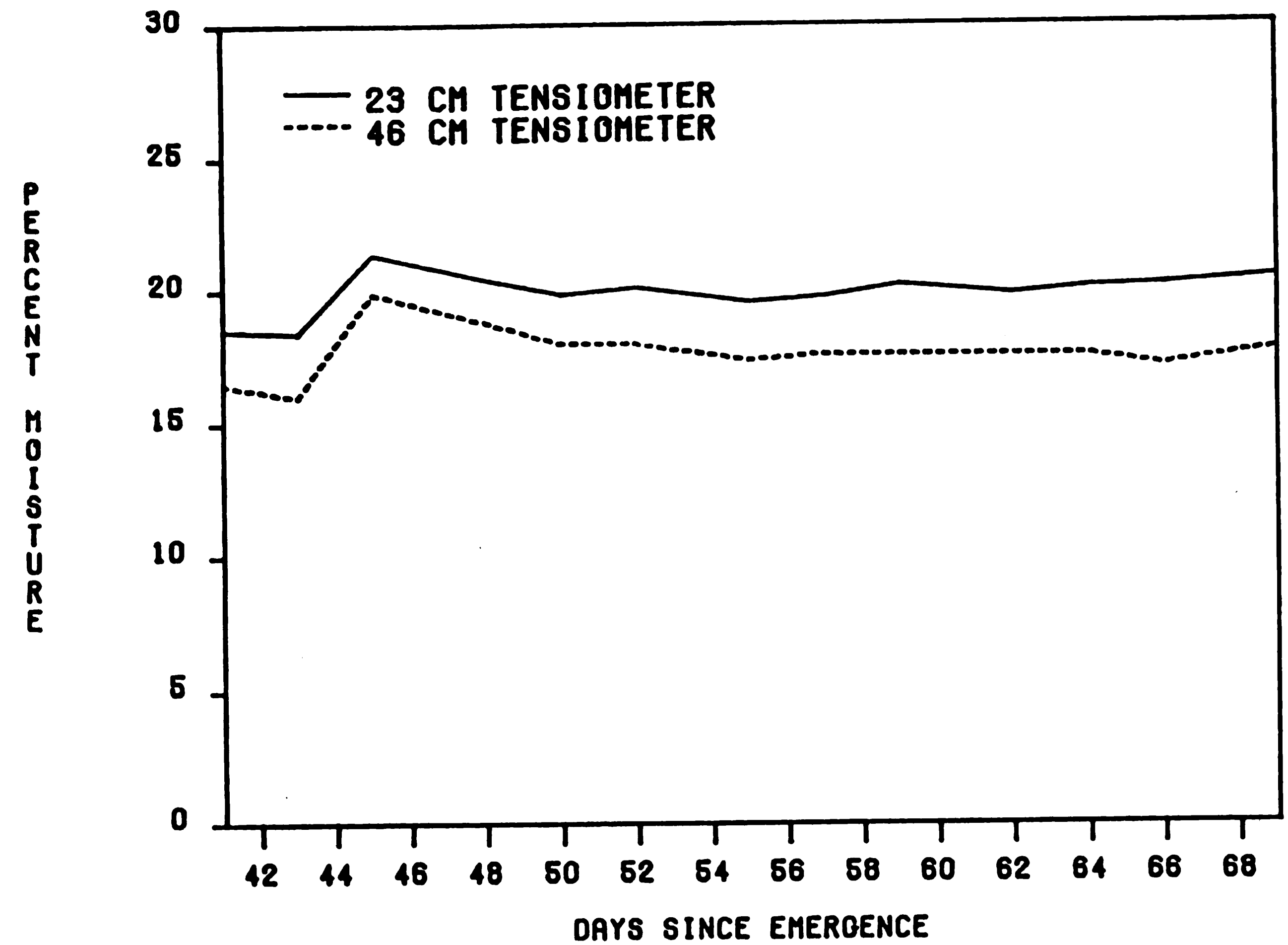

Fig. 17d. Range 3 tensiometer readings converted to volumetric percent moisture.

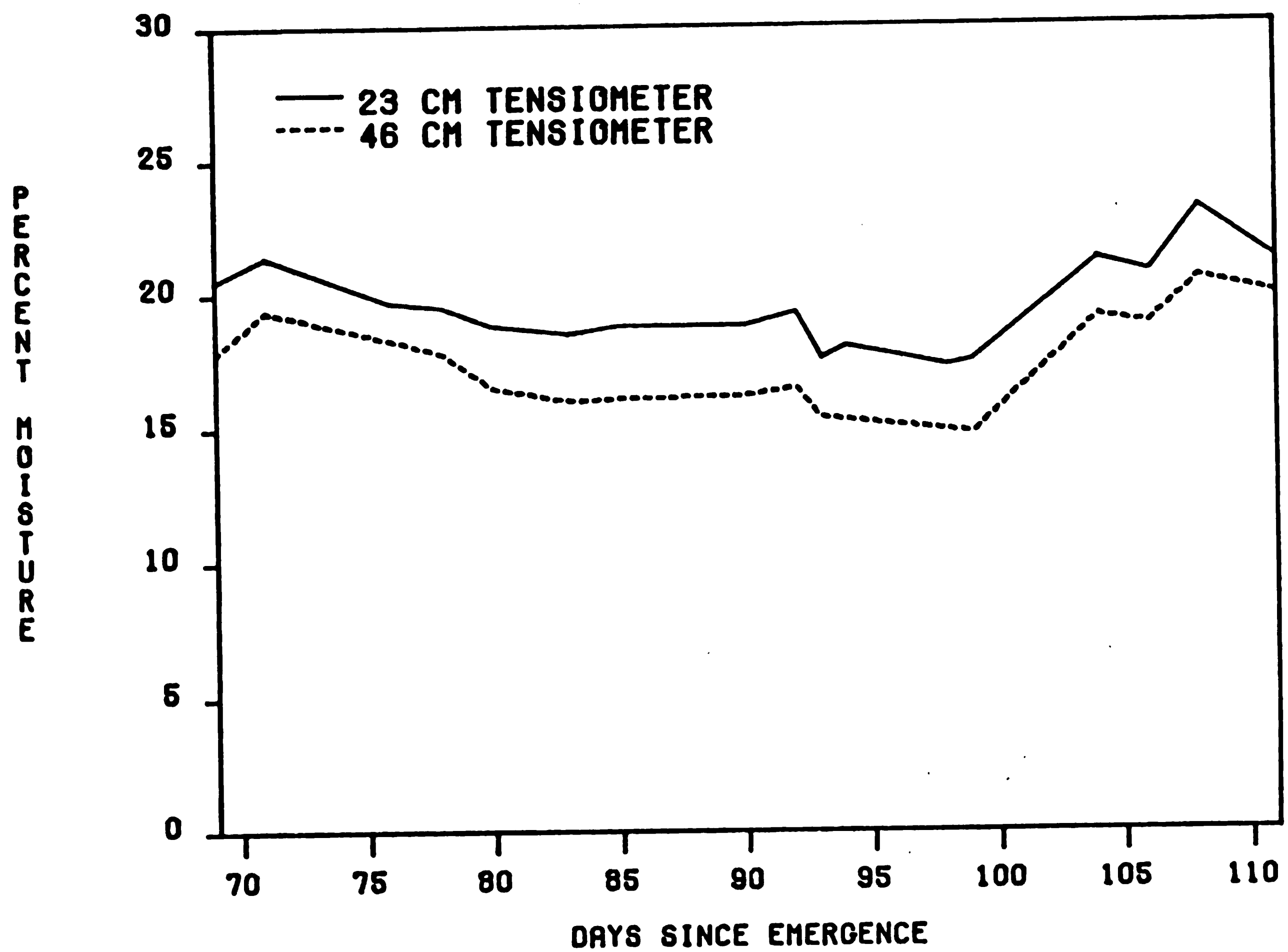

Fig. 18d. Range 3 tensiometer readings converted to volumetric percent moisture.

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